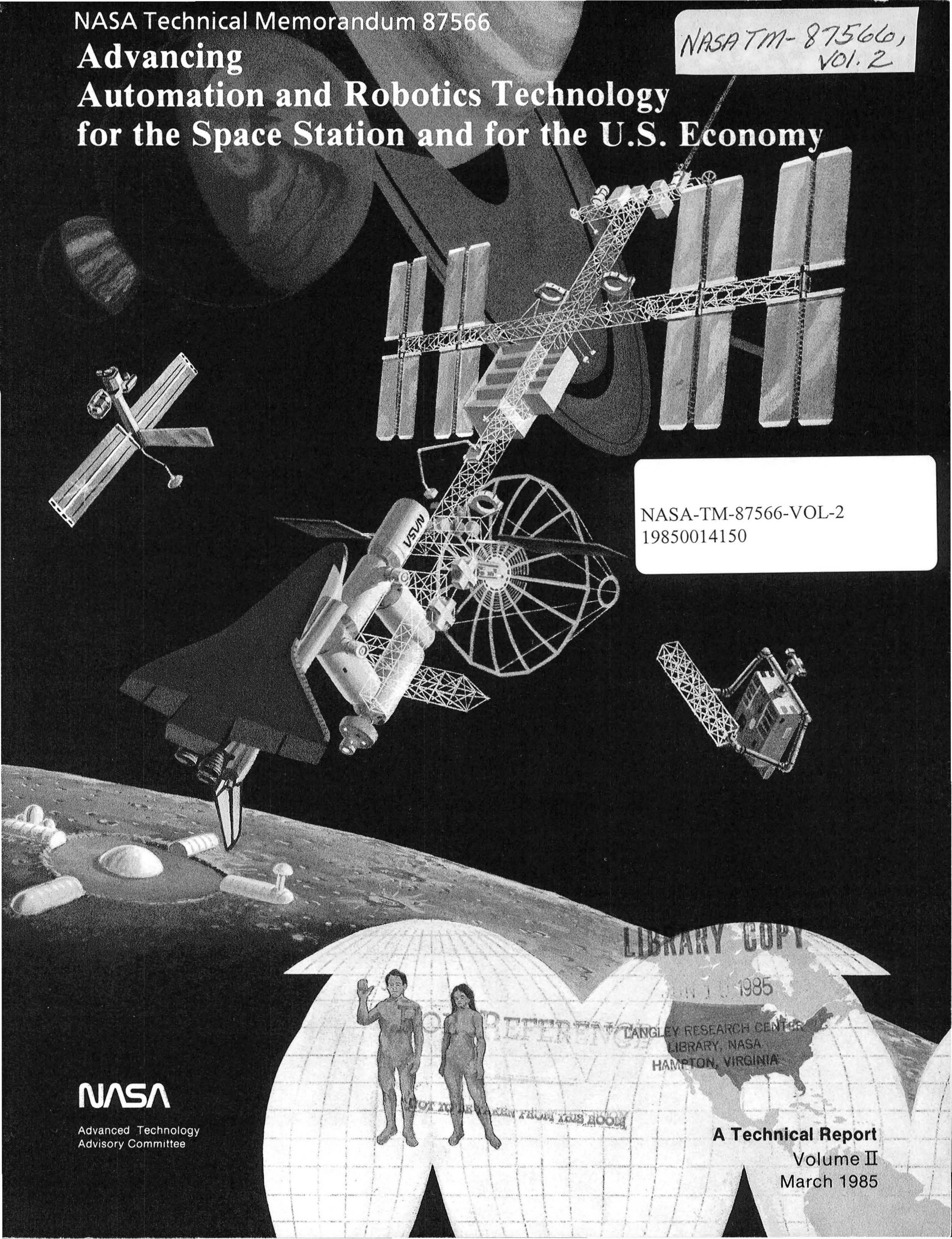
NASA Technical Memorandum 87566

Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy



NASA
Advanced Technology
Advisory Committee

A Technical Report
Volume II
March 1985

The cover painting captures the spirit of the machine intelligence and robotics policy described in this report. Prominently depicted are both the low Earth orbit Space Station complex of platform and core stations and the United States—the two recipients of productivity increases due to creating and using this technology. The man and woman represent each of us benefiting from an improved interaction with more capable machines—a few in space, the majority on Earth. The commercial use of space, made easier by the Space Station, is depicted by low cost, co-orbiting automated manufacturing facilities. The sweeping vision from a lunar manufacturing facility or base to Mars and Saturn and beyond to the deepest reaches of the cosmos pictures a continuing exploration of space.

The painting is an artistic rendition by Raymond J. Bruneau of an original design by Roy L. Magin, both of the Technical Information Branch at the Lyndon B. Johnson Space Center.

TM-87566

ADVANCING AUTOMATION AND ROBOTICS TECHNOLOGY FOR THE SPACE STATION AND FOR THE U. S. ECONOMY

VOLUME II - TECHNICAL REPORT

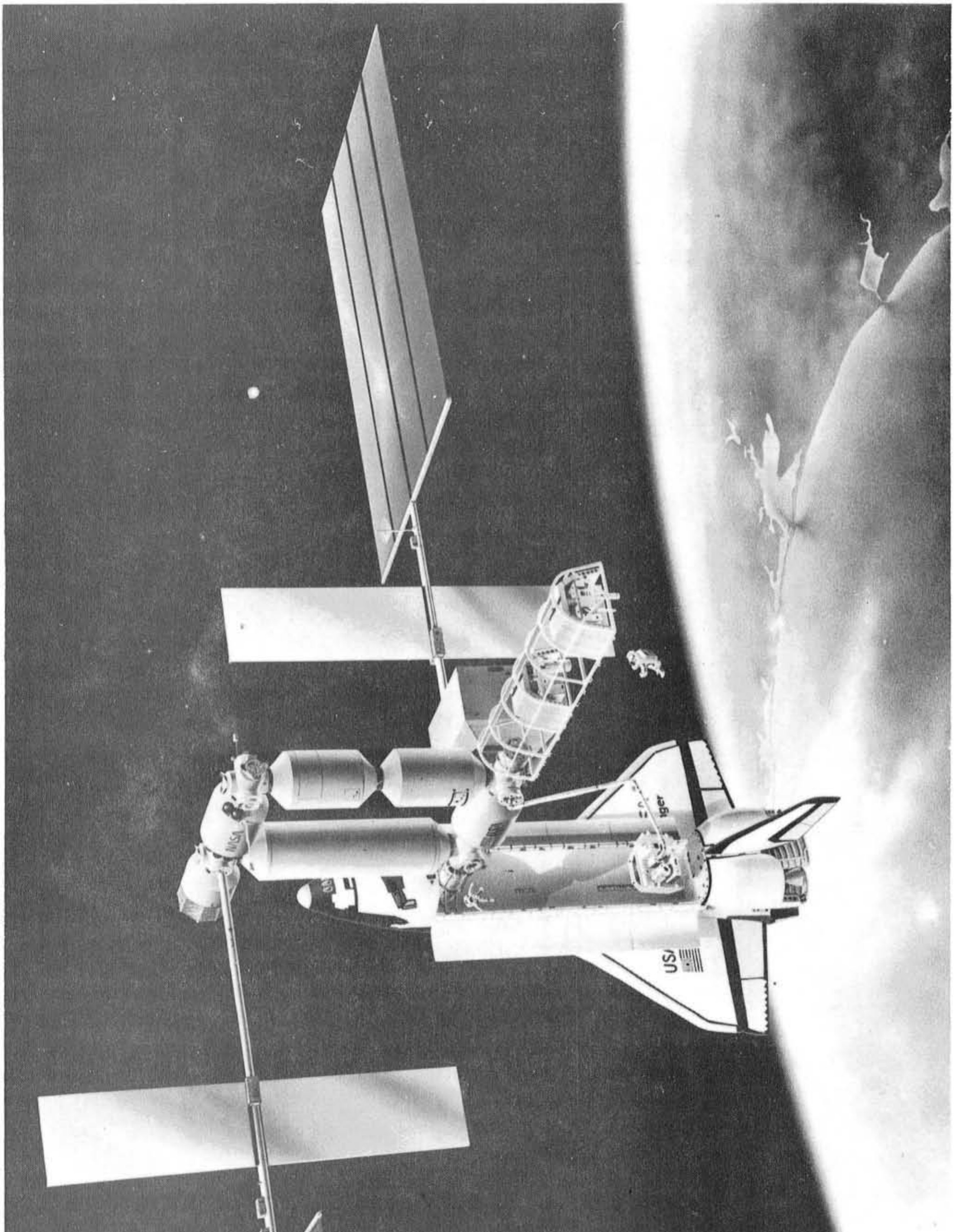
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ADVANCED TECHNOLOGY ADVISORY COMMITTEE

Submitted to the
United States Congress
March 1985

Prepared by

NASA Intercenter Working Group
and JSC Artificial Intelligence Office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PREFACE

In response to Public Law 98-371, dated July 18, 1984, the NASA Advanced Technology Advisory Committee has studied automation and robotics for use in the Space Station and prepared this report to the House and Senate Committees on Appropriations. The study has drawn on work by groups both within NASA and outside NASA, in the academic and industrial communities.

The report is divided into two volumes.

The Executive Overview, Volume I, presents the major findings of the study and recommends to NASA principles for advancing automation and robotics technologies for the benefit of the Space Station and of the U.S. economy in general.

The Technical Report, Volume II (this document), provides background information on automation and robotics technologies and their potential and documents the following:

* The relevant aspects of Space Station design

* Representative examples of automation and robotics applications

* The state of the technology and advances needed

* Considerations for technology transfer to U.S. industry and for space commercialization

Volume II provides guidance for prospective Space Station contractors to direct their efforts toward a planned advance in these technologies.

This report is referenced in the request for proposals for definition and preliminary design of the Space Station. Volume II in particular provides guidance for prospective Space Station contractors to direct their efforts toward a planned advance in these technologies.

In response to an agreement with the Senate Appropriations Committee in April 1984, NASA funded and managed a number of studies in the general area of automation and robotics. These studies were done by academic and industrial specialists working in the field, and they provided important insight to the Advanced Technology Advisory Committee.

An Automation and Robotics Panel, led by the California Space Institute, prepared the report "Automation and Robotics for the National Space Program." Five aerospace firms conducted studies of critical issues (discussed in chapter 5 of this volume). Further, SRI International studied the general state of the technology and areas in which research is needed. The documentation of all of these studies is referenced and should be read in conjunction with this report.

STUDY ORGANIZATION AND PARTICIPATION

In response to the mandate from Congress to address advanced automation and robotics, NASA undertook to enlist as much expertise as was reasonably available. A concerted effort was made to involve aerospace contractors, industry, and universities. The work was structured into three major elements, carried out by the Advanced Technology Advisory Committee, the Automation and Robotics Panel, and by SRI International and aerospace contractors. The organizational methodology used for this Space Station automation study is depicted in figure A. The manager of the study is Dan Herman, NASA Headquarters, and the deputy manager is Victor Anselmo, NASA Headquarters. The chairman of the steering committee for the study is Robert A. Frosch, Vice-President, General Motors Corporation.

The Advanced Technology Advisory Committee was formed pursuant to PL 98-371. The members of the committee, listed in table I, were selected not only because of their professional experience and capability, but because the organizations they represent would be those responsible for assuring a high level of accommodation of automation and robotics on the initial station and its associated platforms. The committee was tasked to consider the charge from Congress, the needs and limitations of the Space Station Program, and the findings of the other studies and also to provide recommendations to NASA.

The California Space Institute (Cal Space) of the University of California formed the Automation and Robotics Panel (ARP), which included representatives of industry, academia, and Government (table II). The panel was to study available and prospective technology and to provide an independent set of recommendations to NASA.

The aerospace contractors involved studied automation and robotics in specific areas as follows:

Boeing	Operator/System Interface
General Electric	Space Manufacturing Concepts
Hughes	Subsystem and Mission Ground Support
Martin Marietta	Autonomous Systems and Assembly
TRW	Satellite Servicing

Because of the limited time available, the contractors were directed to identify "drivers" for advanced automation. They were not asked to address all automation and robotics applications for the evolutionary Space Station but only those believed to be typical.

SRI International provided a technology assessment based on the contractor studies, their own knowledge of the technology, and their anticipation of technology readiness.

An ATAC Support Group (table III) was formed to assist in the effort. The members of the group functioned as a part of the Space Station Automation Study Team, as observers at the ARP meetings, and as major participants in the support to ATAC. This support group assimilated the inputs from various contributors into this report.

The entire process of the Space Station automation study was an iterative one, with many information exchanges. All meetings, presentation documents, and so forth were open to all participants. This effort required and received extraordinary cooperation from the entire study team.

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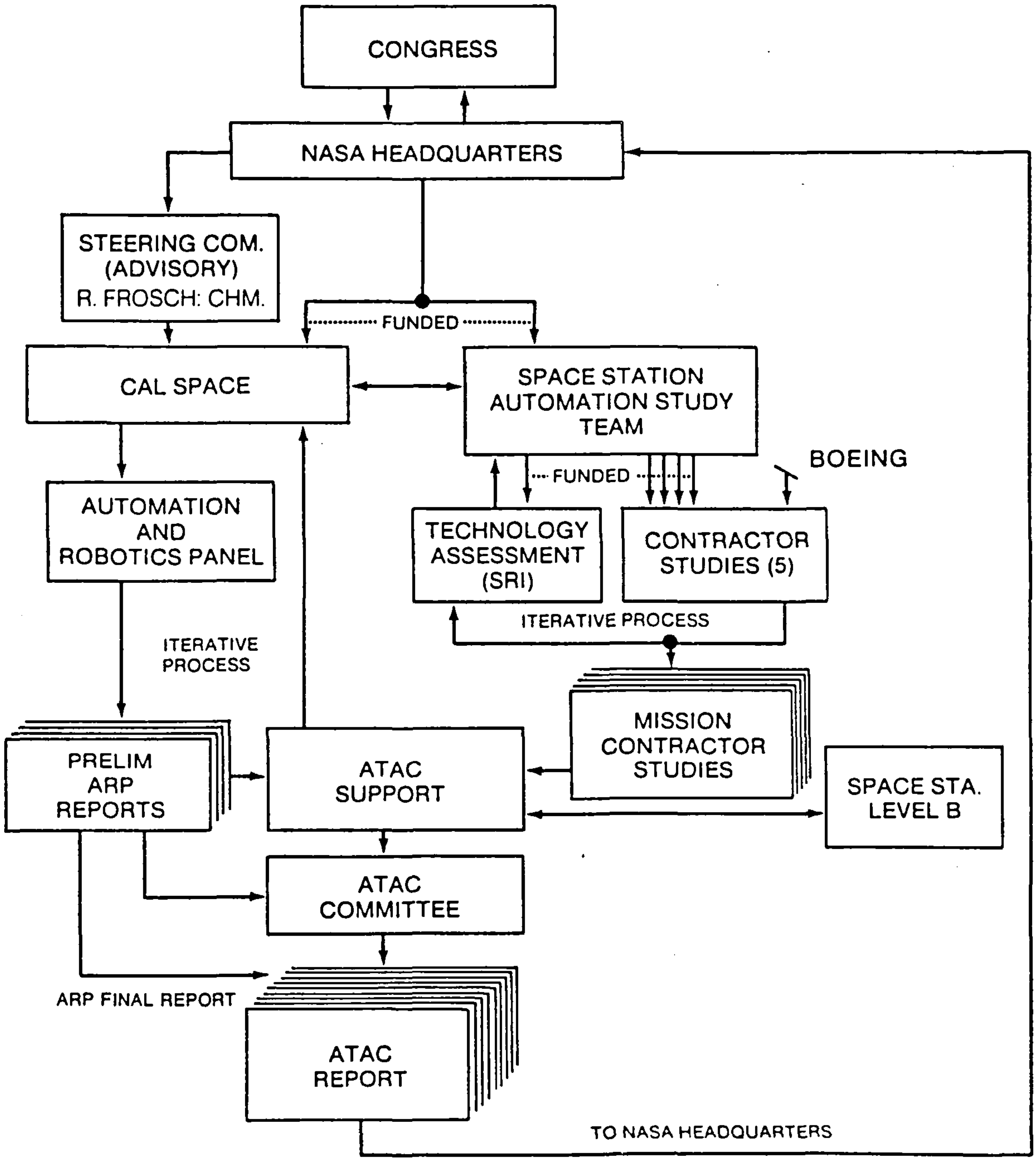

Figure A.- Methodology for the Space Station automation study.

ACKNOWLEDGMENTS

This report was prepared for the NASA Advanced Technology Advisory Committee (ATAC) by the ATAC Support Group and members of the NASA Johnson Space Center Artificial Intelligence Office. The support group, the members of which are listed in table III, provided guidance on the purpose, contents, and organization, as well as making vital contributions to the draft material.

The JSC Artificial Intelligence Office provided the initial draft of the report and integrated comments and revisions to produce the final version. The contributors were

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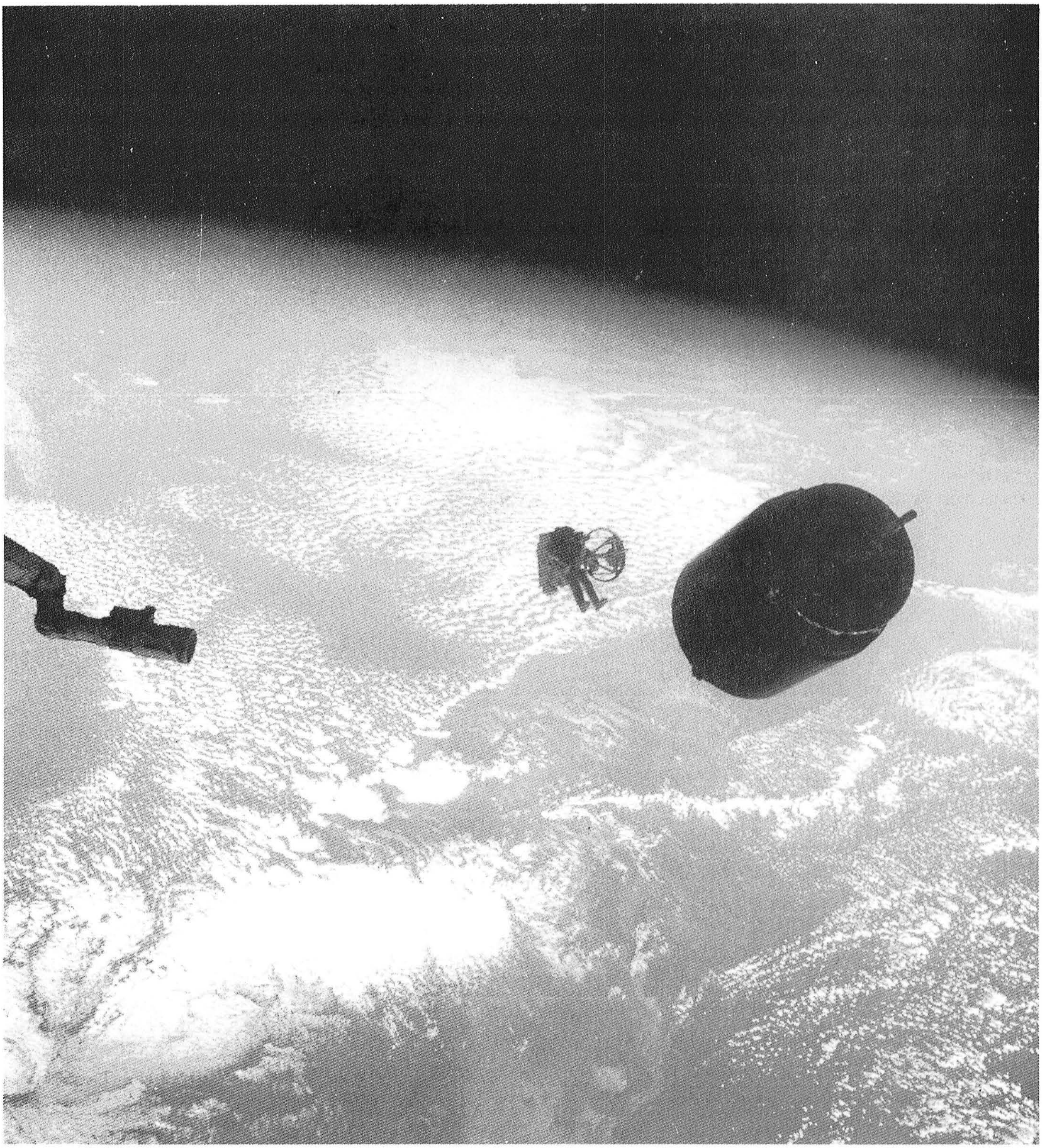

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Chapter 1

INTRODUCTION

"The wealth of nations, which depended upon land, labor, and capital during its agricultural and industrial phases - depended upon natural resources, the accumulation of money, and even upon weaponry - will come in the future to depend upon information, knowledge, and intelligence."
- Feigenbaum and McCorduck, 1984

We are at the beginning of a new era in space which poses significant new challenges as we move into the second 25 years of the U.S. space program. To meet the challenge of critical needs associated with achieving a permanent human presence in space and optimizing the commercial uses of space, the Advanced Technology Advisory Committee (ATAC) recommends that the National Aeronautics and Space Administration (NASA) emphasize an important element in its Space Station Program (SSP) called Automation and Robotics. By seizing an opportunity to leverage recent advances in artificial intelligence, robotics, computer science, and microelectronics, NASA can both use and advance a new generation of machine intelligence and robotics technology. This new technology promises to increase the productivity of humans in space, reduce operating costs, and increase U.S. economic strength over the coming decades. ATAC submits this report with cautious optimism.

CHALLENGES OF AUTOMATION AND ROBOTICS

There are a number of new challenges for the U.S. space program:

* We must make use of the new technologies becoming available to assure effective utilization of our resources.

* We must meet the challenge of international competition in space (a challenge we welcome!).

* We must establish a permanent presence in space.

* We must move from an era centered primarily on space exploration to an era which includes the commercial uses of space.

These new challenges, when considered in their totality, constitute the beginning of a new era - the Space Business Era. They require that we reexamine, revitalize, and initiate imaginative new ways of doing business in two closely interrelated areas: (1) within the Government organization itself, and (2) in our joint industry-Government partnership. The Space Business Era will require Government to expand its space operations from exploration and experimentation to include significant commercial ventures as well. Such commercial ventures will call for a new kind of vendor-customer relationship between Government and industry.

An important reason for a permanent presence in space is the knowledge it will produce. Knowledge about many aspects of science, and the applications of this knowledge in technology development and commerce, will result from the enterprise of building a space station - a set of evolving, multipurpose facilities in space. The facilities envisioned for the Space Station include on-orbit laboratories; permanent observatories; a transportation and communication node; and servicing and repair facilities for spacecraft and manufacturing and assembly equipment. The Space Station is a means of acquiring and exploiting the unique knowledge and products which are made available through continuous access to the benefits of space, including microgravity, high vacuum, and being outside the atmosphere in low-Earth orbit.

A society which can produce highly productive, multipurpose facilities in space may be moving into a so-called "post-industrial society" on the Earth as described by Daniel Bell (Bell, 1976) and others. The "axial principle" of such a post-industrial society is the centrality and codification of

knowledge. Other characteristics of such a society are a new "Intellectual Technology," the spread of a knowledge class, the switch from goods to services, a change in the character of work, and so on. The new intellectual technology for society will include artificial intelligence and robotics. The Space Station Program will both provide and use new knowledge, thus interweaving cause and effect. Congress has mandated that NASA advance the technologies of machine intelligence, robotics, and automation for increasing productivity both on the Space Station and in the U.S. economy. The Space Station Program, as both stimulus and user of this technology to achieve space-related knowledge/productivity goals, will provide a high degree of visibility to the technology.

For this business era of space, the fundamental challenge is to meet the needs of the "customers" (users of space) with facilities enabling maximum productivity and having low start-up costs and low annual operating costs. A facet of this is to minimize the role of humans as operators and to maximize their use as managers. An effective way to meet this challenge may be with a human-machine mix where robotics and advanced automation are integrated into high-reliability systems. Much of the technology required to meet the anticipated needs of the Space Station Program is not currently available. However, it is ATAC's belief that a vigorous research and development activity, if begun immediately, could produce the needed technology. It is largely this future technology base which will be transferable to U.S. industry and which will lead to productivity increases in terrestrial applications.

THE ROLE OF HUMANS IN SPACE

The environment of space is a difficult one, but the promise it holds for new knowledge and new products is immense. Further, there is a great deal we do not understand about either the environment or the potential. It is in just such uncertain circumstances that humans function best.

So, what then is the role of humans in space? The human role should be based on what humans do best, which is use their intelligence to perceive, to understand, to redefine continually what needs to be done on the basis of what has been learned, to take advantage of unforeseen opportunities, to solve unforeseen problems, to save a mission (occasionally), to supervise machines, to adapt with minimal reprogramming, and to acquire, integrate, and interpret multisensory data.

DEFINITIONS

It is useful to define some key terms which will appear throughout the document. "Automation" and "robotics" are much-used, broad terms. However, the fields of automation and robotics have grown from a blending of many technologies, including computer science, sensors, mechanisms, displays, and controls. Therefore, the terms will have somewhat different meanings depending upon the context. For the purpose of this document, we will use the following as working definitions.

<u>Artificial Intelligence</u> is a subfield of computer science concerned with the concepts and methods of symbolic inference by a computer and the symbolic representation of the knowledge to be used in making inferences so as to make a machine behave in ways that humans recognize as "intelligent" behavior in each other.

<u>Automation</u> is the use of machines to control and/or carry out processes in a predefined or modeled set of circumstances without human intervention. Advanced automation, for the purpose of this report, is used to refer to the fields of artificial intelligence, teleoperation, and robotics.

<u>Autonomy</u> is an attribute that allows a system to operate to its specified performance without external intervention for a specified period of time. Fault tolerance and reliability are key features of autonomy.

<u>Expert Systems</u> is a subfield of artificial intelligence concerned with developing computer programs that use knowledge and reasoning techniques in specific problem domains to emulate the decision processes of human experts.

Robotics is the study and use of machines capable of manipulation and/or mobility with some degree of autonomy. The autonomy may be almost complete - as in the case of an industrial manipulator which follows a sequence of preprogrammed moves, or the Viking Lander which carried out sequences of operations during the periods between instructions - or limited, as with teleoperators used for nuclear or undersea operations.

Teleoperation is the study and use of manipulators which receive instructions from a human operator and perform some action based on those instructions at a location remote from the operator.

Telepresence describes a teleoperation situation in which the operator has sufficient cues to feel present at the remote location.

The goal of an evolving, multipurpose facility for producing and using knowledge in space requires an evolving human-machine mix where the machines embody combinations of artificial intelligence, robotics, and teleoperation. The need for an evolving mix is based primarily on (1) the need to redefine continually what needs to be done and how often, on the basis of what has been learned and (2) the need to redefine the roles of man and machine as a result of growing confidence in the machine. Growth in the role of machines may continue from initial operational capability (IOC) to full operational capability (FOC).

This volume includes a list of acronyms and abbreviations, a proposed NASA glossary of terminology in automation and robotics, and a short list of some special terms or jargon peculiar to space systems.

NEED FOR AUTOMATION IN SPACE

The Space Station will, in any event, be highly automated if it is to succeed. A strong thrust to incorporate advanced automation and robotics can increase productivity, lower operating costs, increase flexibility, improve reliability, make an autonomous station feasible, perform tasks unsuited to humans, and reduce hazards. These benefits are achieved in three basic ways: by taking over time-consuming tasks that must otherwise be performed by the crew, by improving the level of performance of those tasks that are still performed or controlled by the crew, and by performing tasks that cannot practicably be done by the crew. The need is addressed in seven categories - productivity, cost, flexibility, reliability, autonomy, suitability, and safety.

Increase Productivity

A major rationale for advanced applications of automation on the Space Station is that it will increase the productivity of the crew. An astronaut in space is a very valuable resource which should be used to best advantage. Automation will not lessen the importance of the astronauts; rather, it will enable them to function more productively in space.

One way automation can help is by freeing humans from repetitive, tedious chores - for example, the many control and monitoring functions to be carried out on the Space Station. Advanced automation methods can take over much of the burden of monitoring and control. Astronaut assistant programs can be used to guide an astronaut through a complex technical task by providing facts and procedural information that would be difficult to remember. For repair of an onboard computer, for example, such a system might contain a data base of design information, suggest tests for the astronaut to try, and present procedures for recovering from the failure. An onboard, computerized inventory-management system can simplify the task of searching for equipment and materials stored on the Station. A corollary to releasing the crew from low-level control and monitoring functions is that morale will be enhanced, and the astronauts will have more time to devote to higher-level decision making and discovery functions.

Another way automation can result in higher productivity is by reducing the need for frequent, detailed control and direction from the ground. If astronauts are more closely involved in planning their own day-to-day activities via an onboard, interactive scheduler, they can make maximum productive

use of their time. When communications with the ground are interrupted, productive operations on the Space Station need not be halted if a high degree of automation is present.

With automatic fault diagnosis and recovery, many component failures can be quickly and reliably detected and backup units placed in operation at once without disturbing the crew. The failed unit can then be replaced or repaired when convenient without disrupting the planned work schedule.

The Space Station will carry many sophisticated and complex devices. For humans to interact efficiently with these devices, the interfaces must be natural and direct. For example, "heads-up" displays, perhaps mounted on helmets and with voice input and output, would leave astronauts free to move about and use their hands while directing a machine. Displays, supported by intelligent data management, could reduce the apparent complexity of an onboard system by presenting data from the system in a condensed, visually informative manner. Developments in the areas of computer graphics, intelligent data base management, natural language, speech synthesis, and speech understanding will be used to accomplish this.

Productivity on the Space Station can also be enhanced by mechanical devices which interact with humans. For instance, a teleoperated or robotic system could be used to assist an astronaut on EVA by holding tools, moving objects into position, grasping objects being worked on, or providing mechanical capabilities a human does not possess.

Lower Operating Cost

Advanced automation can reduce operating costs sufficiently to justify easily and quickly the initial investment. In addition to enhancing crew productivity, cost savings over the life of the station can be realized through lowering the amount of support resources on the ground and extending the lifetimes and versatility of Space Station systems.

Increased Station autonomy can greatly reduce the number of personnel needed for ground control. Intelligent computer-aided instruction can similarly reduce the costs associated with preflight training of the crew; in addition, much training could take place on the Station through embedded training systems. Automation of systems in space can reduce maintenance expenses and extend the useful lifetimes of such systems. Automatic control enables a system to be operated at peak efficiency. Automatic fault diagnosis, isolation, and recovery can allow a device or experiment to remain in operation after a failure without the cost of sending a human to perform repairs or returning the failed equipment to Earth.

Increase Flexibility to Support Innovation

Advanced automation can increase not only the productivity of the crew on the Space Station, but also can increase the flexibility of systems in terms of their capability to support innovation. A system designed for automation will of necessity possess certain characteristics which support technical change and innovation.

The computing power and data storage necessary for automation will be present if required by some new technology. Data communication paths and standard interfaces established for automation will increase flexibility. Modularity of design and interchangeability of parts lead to easier incorporation of new technology.

Improve Reliability

The reliability of the Space Station is characterized by the likelihood of a failure or process interruption, the way in which a failure or interruption occurs, and the effort and time required for the diagnosis, repair, and recovery from the degraded condition. Clearly, failure should be infrequent and graceful and restoration should be smooth and prompt.

While the increased complexity of a highly automated system can be expected to have an adverse effect on component failure rates, automation can improve system reliability in several ways. Systems for monitoring and control do not become tired or irritable as

humans do. Software for automatic fault isolation and recovery can keep a critical system going until an astronaut has time to change out the failed part. Fault-tolerant computing leads to better reliability of all subsystems that rely on computers. In emergency situations, automated systems which respond very rapidly to a crisis can bring the system to a fail-safe condition before extensive damage occurs. The system can then be repaired safely and put back into operation with a minimum of "down time." Without automation humans may be placed more often in pressure-prone situations such as EVA and emergency maintenance in which there is an increased chance of error.

Achieve Autonomy

One of the key engineering guidelines for the Space Station is that it is to be operationally autonomous. Autonomous operation means that the Station could carry out normal operation for some finite period of time without contact with the ground. This will be necessary as insurance against emergency situations where some failure or natural phenomenon disables communications. Moreover, autonomous operations will greatly increase crew productivity because the need for communication with the ground is reduced. The Space Station polar platform will require even higher levels of autonomy because a crew will be present only for special missions. The automation techniques so developed will directly benefit the manned Station. As more functions become automated on the Space Station, more knowledge and control will be transferred from the ground to space, leading to a higher level of autonomy.

To achieve autonomy on the Space Station, automation will be required in several areas. Expert systems are needed to perform many monitoring and control functions requiring complex status analysis and automated decision making so that the Station is less dependent on ground support in these areas. Planning and crew scheduling could be accomplished using similar methods onboard. A health maintenance facility using automated diagnostic instrumentation could increase the ability of the crew to operate independently from the ground. Automated fault diagnosis and recovery are necessary to be able to handle routine repair operations without assistance from the ground.

Increased experience with autonomous systems has allowed clarification of some of the pitfalls in this area. A potential problem is the over-reliance on decision-aiding systems. A person unfamiliar with the system might blindly accept recommendations from the computer, possibly leading to improper decisions. Expert systems can be designed to avoid much of this problem by pointing out the line of reasoning that leads to a particular conclusion.

Perform Tasks Unsuited to Humans Alone

Many tasks can be performed better by machines than by humans. One reason a task may be unsuited for humans is that the task is dangerous, an issue addressed in the next section. Here we consider tasks that can be performed better by machines, either alone or in conjunction with a human.

Machines tend to be better than humans at continuous monitoring; performing precise, repetitive tasks; storing and recalling large amounts of precise data over short periods of time; computing; responding quickly to signals; doing many different things at the same time; and ignoring distractions; and not getting bored or tired.

Machines can be given perceptual abilities outside the range of human capabilities, such as detecting particulate, infrared, and microwave radiation; magnetic fields; absolute temperature; and audio signals beyond the limits of human hearing. In some cases the real world is represented in forms that are more readily interpreted by machines than by humans. For example, thermographs, sonar images, spectrographs, CAD/CAM files, and stress diagrams can be analyzed by machine more naturally than they can be mapped onto the human sensory space and understood by a nonexpert.

In space construction, large forces or long-term, repetitive motions may be required that are difficult for humans. Certain tasks may require more time than an astronaut can spend

in EVA. In some cases a machine can reach spaces that are too small for an astronaut in an MMU. For contingency operations outside the spacecraft, a robot might respond much faster than a human because EVA preparation time would not be necessary.

Reduce Hazards

A final reason for automation on the Space Station is that it can reduce danger to human life.

An increased telepresence capability will reduce the need for sending astronauts on EVA, thereby decreasing the exposure to potentially hazardous situations. In some cases, as at geosynchronous altitude, exposure to radiation is a serious threat. An unmanned Orbit Transfer Vehicle (OTV) with a manipulator package would be an effective alternative.

Work environments in space can pose serious dangers to humans because of the nature of materials or devices involved. Certain fuels are highly toxic or volatile. Some facilities in space will involve extreme temperatures or pressures. Completely automating these environments would remove humans altogether from such potentially dangerous situations, and automatic fault diagnosis and response can reduce the dangers where the crew must occasionally be present.

Despite all precautions, there is always the possibility that accidents will occur. Accidents such as the breakage of a fuel line or an explosion in a materials-processing facility would create environments too hostile for human intervention. Intelligent, general-purpose robots could deal with such emergency situations without danger to human life.

THE STIMULUS FOR THIS REPORT

Congressional Mandate

Conference report 98-867 of the House of Representatives, 98th Congress of the United States, was submitted as documentation of agreements by the two Houses concerning funding for Fiscal Year 1985 (House of Representatives Bill 5713). Amendment No. 39 establishes the Advanced Technology Advisory Committee (ATAC) in conjunction with the Space Station Program. The ATAC is mandated to identify specific Space Station systems which advance technologies not in use in current spacecraft. Additionally, it is the intention of Congress that automation and robotics implementation will not only promote the efficiency of the Space Station, but, by enhancing the technical and scientific base, will also lead to more productive terrestrial applications. The official language of the bill requires submittal of the ATAC report on Advanced Automation and Robotics on or before a deadline of April 1, 1985.

NASA/Industry Coordination

NASA requirements for Space Station automation and robotics, coordinated with the U.S. industrial needs for more efficient production, can play a large part in bringing the country into eminence in these areas. Several factors will be emphasized in space development which heretofore have hindered the progress of automation in industrial applications. The lack of standardization in computer systems has been a principal deterrent. The deficiencies include nonstandard languages and disparate intercommunication techniques. It is felt that an impetus by the government toward more universal computer interfaces and software development capabilities, in support of Space Station requirements, will facilitate wider acceptance of automation by terrestrial industries.

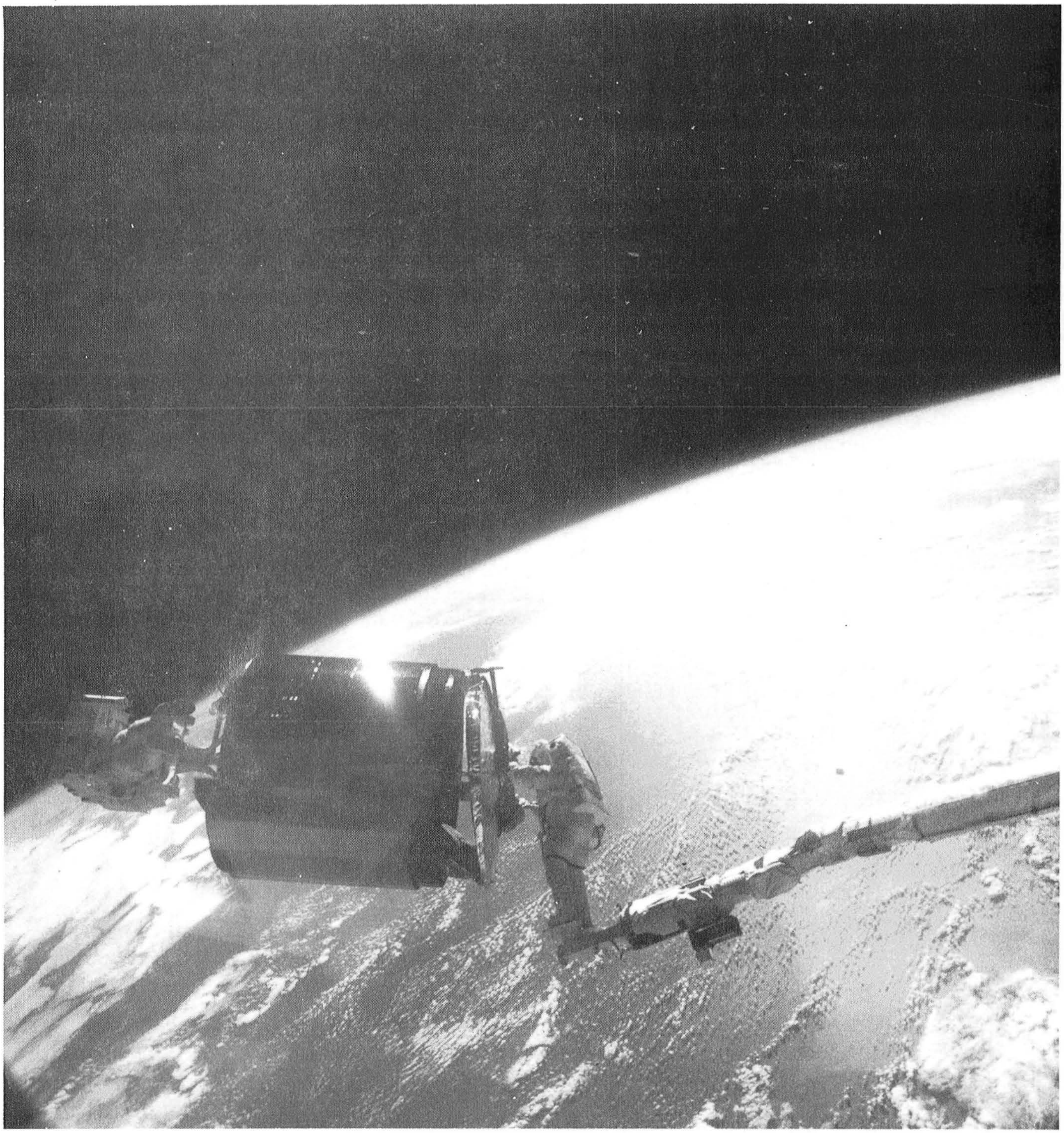
Success in meeting Space Station objectives for fault tolerance and fault recovery techniques will provide a better understanding and acceptance of the benefits of automation/autonomy by the industrial community. The utilization of robots in industry involves considerably different technology in basic design and development; however, research in control techniques and artificial intelligence as they apply to the Space Station is readily exchangeable with ground-based industries. Similarly, the requirement for operator interaction with robots and teleoperators and the resultant interfaces will apply equally to industrial and Space Station implementations.

The NASA Automation and Robotics Panel, led by Cal Space, has been the vehicle for coordination with industry and academia and for communication of their needs and requirements to the ATAC. This panel comprises prominent members of the industrial and academic research community who utilize automation and robotics for research and applications. Universities, national research laboratories, aerospace contractors, nonaerospace industries, the Department of Defense, and NASA support the Panel with regularly scheduled meetings leading toward the preparation of the report "Automation and Robotics for the National Space Program." The panel's recommendations for technology implementation stem from considerable experience in the industrial marketplace and their study of the requirements for Advanced Automation and Robotics for both the IOC Station and the evolutionary Station envisioned for the year 2010.

Identification of New Technologies to Stimulate the Marketplace

NASA has a long tradition in the promotion of ideas and innovations which have resulted in new and improved goods and services for the nation. This promotion and "technology transfer" has, in general, been little recognized. In many instances such ideas have contributed greatly to the needs of the public. Only a small portion of the populace is aware of their origin, yet nearly everyone is affected. Styrofoam insulation is a classic example. Another example is the development of Nuclear Magnetic Resonance imaging techniques, which are now finding wide application in medicine. A voice-controlled wheelchair was made possible by NASA-sponsored advances in voice command systems. These, as well as many other developments, can be traced back to basic research which was performed by industry and promoted by the Government's quest for aerospace applications.

The Space Station will utilize additional new technologies and will develop further applications of existing technologies. In both cases, a stimulus exists for new products and services for terrestrial applications. The exact nature and value of these applications cannot be predicted; however, past experience, as in the examples above, makes it clear that they will come into being.



Chapter 2

AUTOMATION AND ROBOTICS IN USE IN EXISTING SPACECRAFT

Congress has mandated that the automation and robotics technology used in the Space Station should advance the state of the art beyond that used in existing spacecraft. This chapter provides a brief summary of the current state of the art in existing spacecraft. Our present space activities simply would not be possible without automation.

Automation in Earth-orbiting missions consists primarily of (1) fault-tolerant redundancy and readily updatable command sequences in unmanned satellites, (2) additionally limited teleoperators on manned Shuttle missions, and (3) full autonomy with some closed loops on interplanetary missions where mission response times do not allow direct real-time commands. The Viking Mars Project, in particular the associated Lander mission, represents the most complex example of full autonomy undertaken by NASA.

TELEOPERATION/TELEPRESENCE

The state of the art of teleoperation technology as used in existing spacecraft can be exemplified by the Space Shuttle Remote Manipulator System (RMS). Due to lack of dexterity and general-purpose utilization, it is a limited teleoperator. Also, the system does not possess the attributes of telepresence (force/torque reflection and other sensory feedback), although its operation is monitored visually or with TV systems. Force and torque sensors are essentially state of the art and could be implemented if desired. Controllers to accept reflected signal inputs to provide "feel" can be designed with available techniques. The "vision system" used with the RMS consists of out-the-window viewing supplemented by in-situ solid state TV cameras and split-screen CRT's.

Arm control is through a computer software program which translates controller inputs into arm motion. Controller inputs are via conventional spacecraft hand controllers. A supervisory control routine has been implemented which permits the arm to follow a predetermined trajectory. Collision avoidance software was not implemented because of memory limitations.

Other means of controller input, such as master/slave controller of the RMS, were evaluated and rejected because of space limitations and excess complexity.

ROBOTICS

The soil sampler on the Mars Viking Lander is the example application, on U.S. spacecraft, of a system with robotic attributes. An arm, through a preprogrammed sequence initiated by an external stimulus, could locate itself at various surface positions, acquire and retrieve surface samples, and perform trenching operations. About one hundred to several hundred commands were required for each sampler arm task (Soffen, 1977). These commands were developed from stereometric determinations of sample sites occurring in the Lander cameras' image data. Command sequences were verified in simulations using the Science Test Lander. Soil sampler arm motor currents were monitored for scientific interpretation of soil mechanical properties, but not for robotic feedback. The sample analysis system employed a preprogrammed branching logic which permitted decisions, based on data comparisons, as to which branch (or analysis option) was most appropriate to follow.

AUTONOMY/AUTOMATION

The extent to which a spacecraft can operate autonomously can be indicated by the

number of different elementary functions the spacecraft can perform between commands given by humans. The trend of spacecraft automation using this indicator is shown schematically in figure 1, taken from Sagan, 1980.

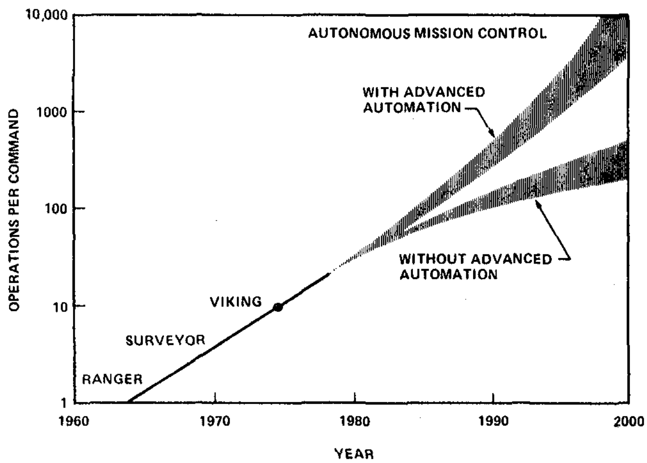


Figure 1.- Trend of spacecraft automation (Sagan, 1980).

In manned spacecraft vehicles, another relative indicator of the degree of automation is in the number and kinds of displays and controls available to the flight crew. The Shuttle Orbiter's Display and Control (D&C) system, which is a human/machine interface, is comprised of some 88 panels containing 1,660 control elements (circuit breakers, toggle switches, pushbuttons) and 646 display elements (meters, digital readouts, event indicators). Four multifunction cathode ray tube (CRT)/keyboard systems are also included. Three of these are in the flight deck panels. Historically, the complexity of spacecraft systems, including the D&C, has increased commensurate with increased complexity in mission and program objectives. For example, the Space Shuttle Program requirements dictate fault tolerance in all systems other than primary structure, thermal protection, and pressure vessels. The avionics systems, to achieve design life goals of 100 missions and 10-year-or-more operational span, are specified to be two-fault tolerant. In comparison, the Gemini (one-mission) spacecraft was controlled by a flight crew of two interfacing with only 286 control elements and 68 display elements mounted on 7 panels.

Other indications of the degree of automation, and ones which also impact the human-machine interface system, are the methods of fault isolation and system reconfiguration. Although the Shuttle Orbiter's avionics computers and sensor systems have the capability to sense faults automatically and reconfigure, the overall redundancy management of the spacecraft systems is largely manual. In fact, because of early concerns over problems of automatic reconfiguration such as generic software errors and "psychotic" computers, a requirement was imposed on the D&C system to permit the crew to manually inhibit or override any automatic redundancy-management actions.

Data Processing System Architectures/ Redundancy Methods

The state of the art in operational spacecraft is largely centralized processing with some level of functional or physical redundancy. A typical centralized architecture is that of the Space Shuttle which operates four computers in a redundant set. Each computer monitors the other's outputs. Voting logic in the set allows an errant computer to be voted off-line with the voting matrix communicated to the crew. The four primary computers all operate from the same software. Software redundancy, or the safeguard against generic errors, is provided for critical mission phases by a Backup Flight System (BFS) in a fifth computer. The BFS software was designed and coded by a group separate from the primary software supplier. Flight software testing is a major hurdle where a large number of changes must be accommodated. A start/stop simulation capability at the instruction-step level is critical for testing.

Some operational unmanned spacecraft and satellite systems are decentralized to some extent with processing dedicated to major functions such as command and control and attitude control. Fault tolerance is through block redundancy which can be active-standby, active-active, or both. For example, the Defense Meteorological Satellite Program (DMSP) satellite uses standby redundancy in most of its subsystems. The Voyager's

Attitude Control Subsystem uses an unpowered standby, whereas the Command and Control Subsystem (CCS) uses a powered spare to monitor the on-line unit. More decentralized, or distributed, architectures are appearing in developmental and planned spacecraft.

Fault Management

Test equipment is frequently built into hardware and software to detect failures or out-of-limit conditions. With physical redundancy, cross-checking permits one unit to monitor the primary controller (Voyager CCS) or multiple units to monitor each other (Space Shuttle Data Processing System). In instances where a level of functional redundancy is available in another system, the alternate system may detect possible faults in the primary system. For example, attitude may be sensed by a system with other primary functions and be able to infer information about the health of the primary precision attitude control system.

Ground procedures are used to detect and isolate failure. One such procedure is to require that special tests be run on the vehicle. Another is long-term trend analysis of telemetry or maintenance recorder data, which may be able to detect unit degradation or wear-out problems.

A technique commonly used upon detection of a fault in near-Earth satellites is to place the spacecraft automatically in a "safe mode." If, for instance, the spacecraft is powered by solar arrays, the arrays are pointed to the sun for maximum power and all nonessential power use is stopped. Ground analysis of the problem is employed to develop a most likely solution. The solution can be to switch to a redundant standby unit or to plan alternate operational sequences, or "work-arounds," that can be transmitted to the spacecraft. In manned systems, onboard manual reconfiguration has been routinely employed.

Automatic fault management is used in critical mission phases or in instances where it is essential to continue the nominal mission without loss of performance. The Space Shuttle's quadruply redundant computers will automatically vote an errant computer off-line. Avionics system sensors can also be reconfigured automatically. An example of the state of the art in planetary spacecraft is that of the undervoltage recovery function on the Galileo. The automated function, after detecting a system undervoltage condition, will reduce power usage. Then, for a particular mission phase, it will decide which power loads are appropriate and add such loads back on-line.

Space Shuttle fault analysis and isolation operations are largely manual. The Shuttle Orbiter has in excess of 3,700 in-flight measurement points of which 1,600 are displayed to the crew via dedicated meters and CRT displays; 2,700 are telemetered to the ground. To isolate a system fault below the level indicated on the displays, the flight crew and/or the ground engineers are required to refer to documents containing the detailed system schematics. Expert system technology, with its ability to provide complex logic traceability and analysis methodology in software systems, will materially reduce operational workloads and training requirements.

Extent of Autonomy

The first level of autonomy is generally considered to be "closed loop control." In such a situation, sequences of instructions are stored and executed upon initiation by a single stimulus. A higher level of autonomy is one able to operate on external information. For example, a device which scans the stars and automatically "locks on" a particular star provides information on spacecraft attitude - information which could then be used in a trajectory adjustment. These levels of autonomy with such "automated" functions are common on manned and unmanned spacecraft.

The expected growth of autonomy without intelligent systems is illustrated in figure 2 (Evans and Gajewski, 1985). This growth is correlatable to onboard computer capability, and may be exemplified by the Mariner vehicles which had five automated routines implemented in subsystem hardware. The Galileo spacecraft will have in excess of 200 automated routines, largely implemented by software. This growth in autonomy is closely

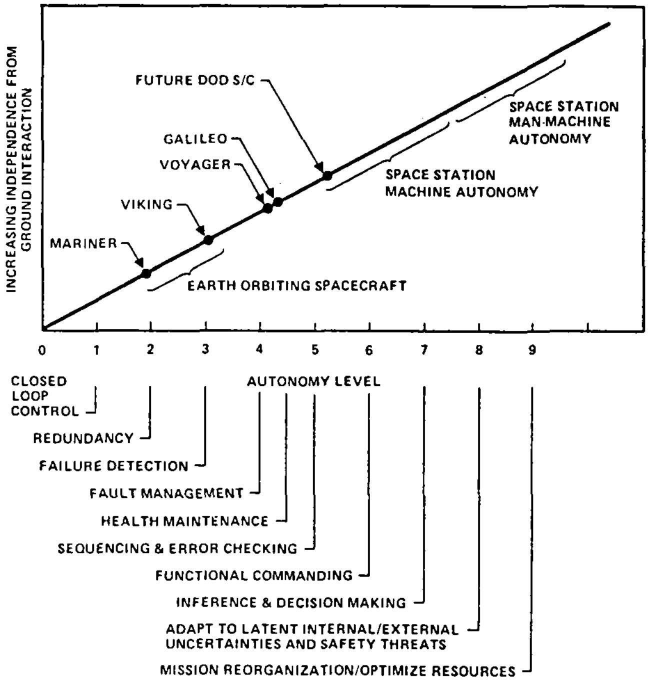


Figure 2.- Autonomy capability levels (Evans and Gajewski, 1985).

correlated to the computational capacity on the spacecraft. In the case of Galileo, about 10 percent of the vehicle's computer capacity is used for automated routines. A similar trend is found in the manned spacecraft program.

AUTONOMY IN EXISTING INTERPLANETARY SPACECRAFT

The Viking Mars Project is NASA's most ambitious achievement in fully autonomous missions. The need for full autonomy in all phases of mission operations was dictated by mission response times of 1 day to 2 weeks. The Viking Landers are especially noteworthy as examples of autonomous operations because of the difficulty and diversity of the tasks which were automated. Even the critical landing sequence had to be performed autonomously with final descent control being exercised by the Lander radar and computer systems. An exposition of autonomous operations is quoted directly from Soffen, 1977:

"The landers were built so that they could operate completely autonomously. At the time of landing, the onboard computers had instructions for performing many days of operations if we were not able to command the lander. In such an event it would have carried out a complete mission, taking pictures, getting samples from a preselected site, analyzing them, recording the weather and seismometry, and relaying the data back to earth. Fortunately, both landers operated flawlessly, and this preprogrammed mission was overwritten beginning with the first command link. Many elements that could cause a total loss such as power, communication, data, etc. were built with redundant units to avoid any single point failure. This was fortunate in the case of Viking 2 when one of the battery chargers failed during cruise. Failure on each spacecraft of one of the command receivers has borne out the wisdom of redundant systems. It was recognized that besides providing the scientific data the cameras would become one of the major tools in solving mechanical problems that occurred. Indeed, this proved to be the case time after time when we had trouble with the mechanical parts such as the sampling arm and the antenna.

"One of the most important requirements for performing the lander part of the mission was the ability to respond to the data. Since virtually nothing was known of the local surface topology, chemistry, or biology prior to the Viking landing, it was essential to be able to modify the experiments as they were progressing. This is the very nature of exploration and the place where the scientist plays a vital role. Our ability to receive data, interpret it, and make changes in our planned strategy normally required about two weeks. That was the time needed for preparing the software, for checking it to prevent errors that could be disastrous, and for sending and verifying the commands. (Of course, laboratory and field science on the earth is done differently, but one must remember that the automated laboratory is over 400,000,000 km away, operating by itself with our ability to command it only once a day at best!)...."

Autonomous operations of the Viking Orbiters were considerably less complex. These are summarized by the following

quotation on command and instrument operation from Snyder, 1977:

"The computer command system (CCS) consists of two identical and independent data processors which receive and store all commands from earth and control everything that the spacecraft does. Each processor contains a 4096 word memory, and for data acquisition sequences, only one processor is used. This relatively large memory and the capability of reprogramming it during flight give to Viking the capability for much greater flexibility of observation sequences than any of its Mariner antecedents had. The memory is partitioned such that a maximum of 1500 words are available for each command load of ground commands to operate the orbiter, and during the primary mission it was the rule that initial planning would use no more than 1200 of these. Since it was not feasible to predict in advance precisely how many command words would be required, this limitation assured that the command generation process could proceed expeditiously and that planned observations would not have to be dropped at the last minute because they would not fit.

"The command words not only must specify how, when, and for what duration each of the science instruments operates but also must control the motions of the scan platform, any spacecraft maneuvers that occur, the tape recorders during both recording and playback of the data, and any switching between celestial and inertial attitude reference that may be required by the intermittent presence in the star sensor of stray light from Mars, Phobos, or Deimos. The command word limitation is usually the factor that constrains the quantity of observations that can be made. (COMMENT: The author notes the exception to this is the picture quantity which is limited by tape storage and telemetry. This observation occurs later in a portion of the text not quoted.) *This constraint was fairly comfortable when command loads were 2 days apart at times during the primary mission but quite uncomfortable for 4- or 5-day loads; when loads were separated by a week or more, very large gaps in the desirable coverage of the planet must be accepted.*

"The detailed sequencing of the orbiter science instruments is accomplished by the flight data subsystem (FDS) in response to the general instructions of the CCS. The FDS performs all the data handling for all orbiter subsystems...The FDS controls data acquisition modes, data rates and formats, gains settings, etc. From every subsystem it receives data, converts them from analog to digital, combines them with other data in the proper format, and routes them to storage or to immediate transmission...."

The use of autonomy in other interplanetary spacecraft is largely through the execution of a set of established procedures or algorithms or through onboard fault management techniques. The following discussion emphasizes procedures onboard recent interplanetary spacecraft.

The intelligent operation of a spacecraft involves a cycle of decision making, given the current state and the goals of the system, and the execution of tasks needed to accomplish those goals. Decision making for a spacecraft is necessary in several areas. At the lowest level are self-regulating processes (attitude, temperature, measurement biases, etc.). Such processes are frequently excluded from the discussion of autonomy unless a degree of external intervention is necessitated by the lack of such features. Other autonomy applications are logical in nature, but also relatively simple, such as the selection of appropriate attitude reference sensors given the environment of the spacecraft. High on the scale of complexity are processes which require balancing a number of factors. For example, a very involved sequence of actions must be planned for complicated events like planet encounters and trajectory changes. A broad spectrum of processes of intermediate complexity can be cited.

The functions which have been made autonomous on recent spacecraft critical to the safety of the spacecraft have been those for which cost studies showed advantages to spacecraft implementation in comparison with ground-based operation, or those which were critical to the safety of the spacecraft and the

accomplishment of its prime objectives. Among the specific items automated in current designs, at least to some extent beyond simple self-regulation, are fault diagnosis, reconfiguration and critical sequence recovery, adaptive attitude reference selection, and tape management.

The principal barriers to autonomy levels greater than this has thus far been the shortage of computational resources and the lack of adequate tools to assist in the implementation of autonomous behavior. Existing implementations have been coarsely crafted and imperative in nature, certainly not representative of the latest in artificial intelligence technology, but they have been effective because of the care and skill of their creators. The rather laborious approach involved is best illustrated by describing the extent to which current implementations have progressed relative to future expectations.

The abstract ideal implementation of an autonomous system would contain some seat of "intelligence" in which would reside a dynamic model of pertinent system features, measurements to monitor the system, a set of goals and restrictions, and the logical tools to infer from these components the best course of future action. In current implementations, many compromises to this ideal have been made. By far the most ambitious efforts to date have been devoted to the autonomous maintenance of spacecraft safety and prime objectives in the presence of faults. (This is not to be confused with various fault-tolerant implementations which rely on simultaneous operation of redundant systems. Such implementations cannot be applied universally because of resource constraints or impracticality, nor would they be considered autonomous.) The resulting software for current implementations contains no system model or explicitly stated high-level goals and constraints, but rather has reduced the abstract ideal to a simple set of "if-then" rules.

These implementations were accomplished essentially by a predecision methodology whereby engineers mentally exercised as many potential fault and recovery scenarios as possible using their understanding of spacecraft behavior and mission goals and constraints to arrive at an optimized set of test measurements and preprogrammed responses. That is, they anticipated the responses that an ideal system might have made to a variety of failure circumstances, and then simplified and combined these responses to the extent possible while maintaining a level of fault coverage deemed adequate for the mission.

The operational disadvantage of this approach is that the responses taken are often overreactions resulting in spacecraft performance loss or missed opportunities. Furthermore, coverage is incomplete, potentially causing unnecessary risk to the spacecraft.

Another disadvantage is that this is an expensive approach which has been stretched nearly to its capacity to deal with current spacecraft designs. Evolution of more complex systems will force a transition to autonomy implementations closer to the ideal. The technology to enable this is becoming available in the form of expert system development tools, more capable computers, and developments in robotics. These systems will show much more finesse and scope of application while providing an opportunity for substantial cost savings.

Near-term advances in onboard spacecraft autonomy resulting from this new technology can be expected in the following areas: expansion of self-regulation to virtually all physical plants in the system, autonomous navigation and maneuver planning, adaptive collection and screening of scientific data, and the autonomous execution of simple repairs to remote systems.

Table 1 gives descriptions of fault-tolerant algorithms that have been used on recent interplanetary spacecraft projects (including the yet-to-be-launched Galileo).

There is currently little automation in ground operations of interplanetary spacecraft, although this has recently been identified as an area that can receive considerable cost benefit from automation. Demonstration programs using expert systems

in the areas of planning, scheduling, and diagnostics are currently available in NASA, but none of these programs are fully integrated into operations at this time.

TABLE 1.- FAULT-TOLERANT ALGORITHMS USED ON INTERPLANETARY SPACECRAFT

Algorithm	Description
CCS Errors Subsystem	Responded to anomalous Command Computer System (CCS) hardware or software conditions. Normally placed the CCS in a wait state (except during a Planetary Orbit Insertion maneuver).
Planetary Orbit Insertion Power Transient	Provided a means to continue CCS execution of the orbit insertion maneuver in the presence of a spacecraft power transient or attitude control electronics power changeover.
Command Loss	Assumed a spacecraft failure if a command was not processed in a specified number of hours. Systematically switched redundant element until a valid command was received by the CCS.
Roll Reference Loss	Responded to a loss of Canopus reference star by commanding a flyback and sweep of the Canopus tracker instantaneous field of view to search for the star within the tracker's field of view followed by a roll of the spacecraft to search for the star.
ACE Power Changeover	Caused a switch to the redundant Attitude Control Electronics (ACE) under specific fault conditions.
Battery Charger Disconnect	Monitored the temperature of each of two batteries during charging. Disconnected a battery charger from its respective battery if an over-temperature condition was detected.
Share Mode	Determined that the spacecraft was in a share mode and shed preassigned loads to allow the boost converter to boost the solar array voltage to the higher operating point.
Pressurant Regulator Failure	Detected a propulsion regulator leak and isolated the regulator from a high-pressure helium supply before the propellant tank relief valves could actuate.
Battery Discharge Monitor	Monitored discharge current of two batteries during occultation and configured the spacecraft to a safe state if state of charge was below a safe level due to loss of one battery.
Power Check	Configured the spacecraft to a safe power state in the event of an undervoltage condition, a main-to-standby inverter switch, or a CCS tolerance detector trip.
IRIS Power	Selected the infrared interferometer spectrometer and radiometer subsystem (IRIS) standby redundant heater unit if the prime unit failed.

TABLE 1.- Continued.

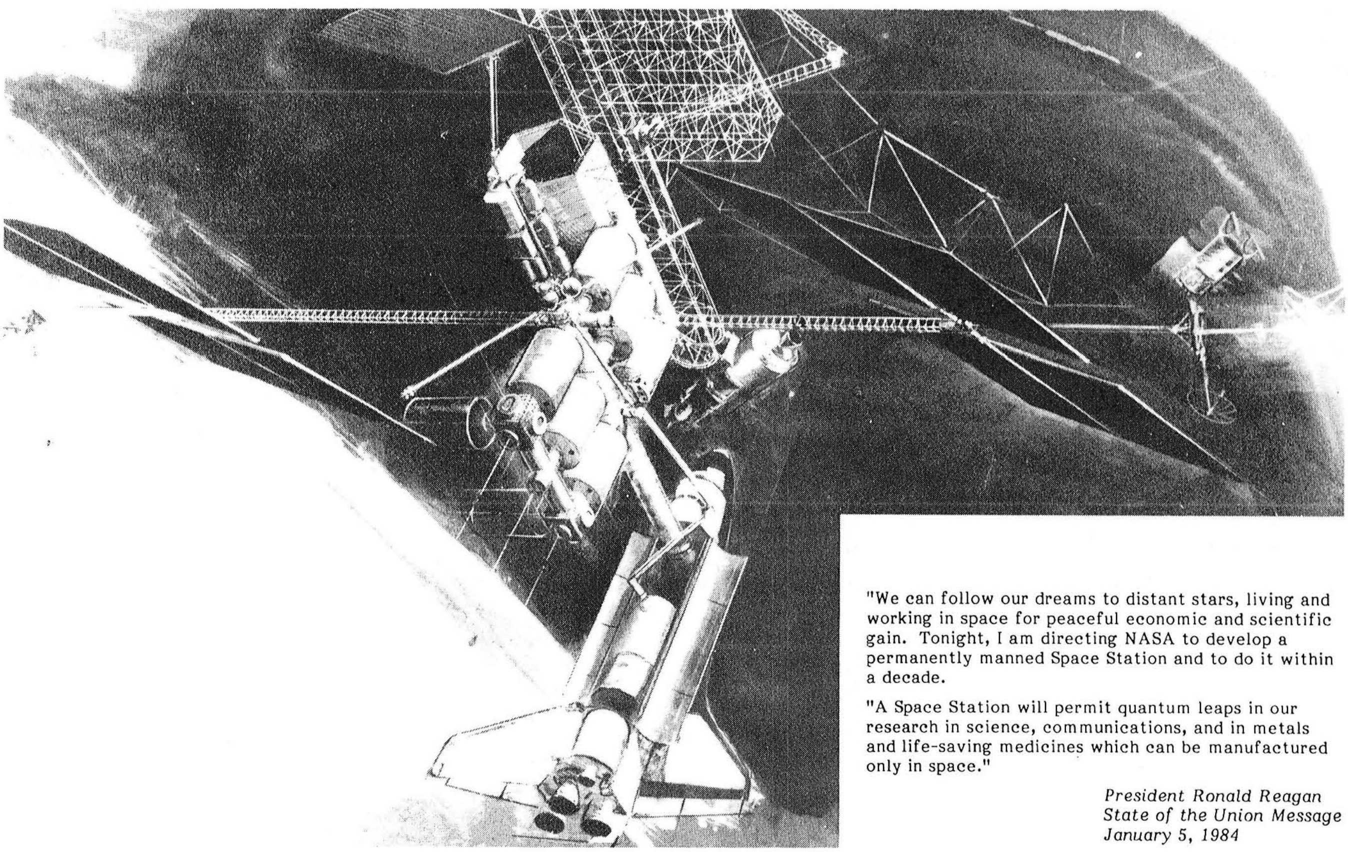
Algorithm	Description
AACS Power Code Processing	Allowed the CCS to respond to power codes from the Attitude and Articulation Control Subsystem (AACS). This was a "handshake" interface that allowed the CCS to monitor the health of the AACS computer and to respond to command redundant or peripheral hardware during normal operation.
Tandem and Turn Support	Verified the integrity of the CCS and AACS prior to critical functions, including turns and trajectory correction maneuvers.
Heartbeat Generator Self-Test Control	Provided a heartbeat check of the AACS-CCS and communication link. Also acted as a performance check on the AACS processor.
Omen Power Code	Issued a power code to CCS indicating detection of a serious fault in AACS. Resulted in saving subsequent power codes for ground analysis. Also inhibited certain functions such as trajectory correction maneuvers.
Celestial-Sensor Fault Detection/ Protection	Monitored operations of the sun sensor and Canopus star tracker. On detection of error, triggered the reacquisition of celestial references and swapped AACS redundant elements.
Autonomous Battery Charging	Autonomously recharged the batteries after solar occultation by monitoring battery temperature.
Science Power On	Prevented damage to science instruments from power transient at turn-on by monitoring current. The instrument was turned off if an over-current was detected.
Receiver Switch	Protected against a receiver failure during extended occultation by monitoring oscillator current and switching to the backup receiver if current fell below a preset level.
Downlink Off	Ensured that the spacecraft transmitter would be turned off at end of mission in the event of loss of command capability.
Accelerometer Monitor	Terminated on the propulsion burn-to-depletion test performed at the end of the mission by monitoring the accelerometer count and commanding engine shutdown when spacecraft acceleration dropped a preset amount.
Automatic Leak Clearing	Monitored position error to detect gas jet leaks and caused jets to actuate in an attempt to clear the leak.
Stray Light	Monitored the Canopus star tracker initiated sequences to prevent damage to the tracker and to acquire or maintain star reference after stray light exposure.

TABLE 1.- Continued.

Algorithm	Description
Low-Rate Engineering Telemetry	Extracted selected data from the telemetry stream for use in fault protection algorithms.
Radio Frequency Loss	Restored either S-band or X-band (or both downlinks) subsequent to a failure of either an exciter or transmitter.
Power Supply Fail	Checked power monitors in the AACS and initiated a swap of redundant elements if a fault was detected.
Memory Refresh Fail	Monitored the plated wire memory cell refresh performed by the AACS processor. Initiated a processor swap if the refresh process failed.
Trajectory Correction and Attitude Propulsion Unit Failure	Performed thruster pulse-rate and spacecraft angular position error checks to detect failures in thrusters. Switched redundant thrusters or AACS interface or processor units if fault was suspected.
Gyro Fault Protection	Monitored gyro warmup and compared outputs during operation to determine faults. Swapped redundant gyro and AACS elements if a gyro fault was detected.
Scan Platform Slew Fault Detection/ Protection	Software timer in AACS to detect slews which exceeded time allowed and prevented actuators from driving against stops. CCS response depended on frequency of fault occurrence.
Command Parity Fail	Performed a parity check in AACS on commands from CCS. If a parity error was detected, transmitted a power code to CCS and did not respond to the commands.
Command Sequence Fail	Protected against false commands to AACS/CCS interface and AACS processor and interface unit operation. Persistent absence of power code echoes resulted in swap of AACS elements.
Bad/No Echo Response	AACS power codes were echoed by CCS to test AACS/CCS interface and AACS processor and interface unit operation. Persistent absense of power code echoes resulted in swap of AACS elements.
Turn Complete and Maneuver Turn Abort	AACS aborted any turn if the sum of pitch, yaw, and roll exceeded 6°. Also rejected any turn commands if a turn was in progress.
Self-Test	AACS conducted a self-test of the processor on request from CCS. If unsuccessful, a processor swap was ordered.
Catastrophe Handler/ Processor Faults	AACS initiated interface unit and processor swaps if earlier switch to redundant element had failed to correct a fault.

TABLE 1.- Concluded.

Algorithm	Description
Propulsion Subsystem Over-Pressure	This algorithm protects the propulsion system from failures which can result in a large helium pressurant loss.
AACS Alert Code Monitor	This algorithm monitors the status of a number of attitude control conditions. A tailored response is provided for each alert code. Presently, 12 alert codes have been identified.
Temperature Monitor	This algorithm responds to the temperature of selected spacecraft elements and activates or deactivates electrical heaters to maintain proper thermal control.
Science Monitor	This algorithm responds to "ill health" indications from selected science instruments by deactivating the main power and activating the replacement heater power.



"We can follow our dreams to distant stars, living and working in space for peaceful economic and scientific gain. Tonight, I am directing NASA to develop a permanently manned Space Station and to do it within a decade.

"A Space Station will permit quantum leaps in our research in science, communications, and in metals and life-saving medicines which can be manufactured only in space."

President Ronald Reagan
State of the Union Message
January 5, 1984

Chapter 3

THE SPACE STATION PROGRAM

This section gives a brief overview of the Space Station Program (SSP). SSP elements and systems are described for both the initial operational capability (IOC) and the full operational capability (FOC). A preliminary operations approach is also summarized. Readers familiar with the SSP may proceed to Chapter 4.

BACKGROUND

The strength of the U.S. economy is closely linked to advances in technology. Keeping the economy healthy requires a continuing investment in new technology. One of NASA's reasons for existence is to preserve America's leadership in technology. The NSTS (Shuttle) has been a major step in technology leadership. Its development is complete and the system is now operational, providing the United States with effective transportation to Earth orbit.

The next logical step to build on previous national investments in space research is a space station. A space station also provides an opportunity for cooperative efforts with other countries. For example, it is a logical extension of the cooperative work with the Europeans on Spacelab. At the time the President announced his Space Station Program decision, he invited America's friends and allies to participate in the program. Thus, a major aspect of the program is to bring about participation of international partners as builders, users, and operators of the Space Station Program elements.

The Space Station Program will evolve in an orderly manner from an initial capability in the early 1990's to a much improved capability in the year 2000 and beyond. The indefinite life of the Space Station Program imposes a requirement for exploiting changes in technology. As new technology evolves and as new mission requirements are established, they will be incorporated into the existing system. Thus the Space Station Program design must be capable of accommodating such changes. As the Space Station Program capability grows, it will accommodate increased levels of autonomy and automation/robotics and attendant increases in human productivity.

The initial Space Station Program capability (NASA, 1984e) provides the following:

* Laboratory provisions for research, development, and demonstration in a pressurized environment with capability for continuous manned interaction and external attachments to which unpressurized payloads or pressurized modules may be connected

* Crew habitation provisions for a crew of six, including workstations, personal hygiene facilities, private quarters, and a ward room and galley that meet essential health and recreational needs

* Provisions for the supply and control of electrical power, thermal control, information and data management, communications, attitude control, and orbit altitude maintenance

* Provisions for berthing the Shuttle (National Space Transportation System) with the Space Station, for connecting major Space Station systems, and for storing and servicing the crew space suits

* Provisions for accommodating resupply of payloads and consumable items, facilities for crew hygiene, processing and storage of material, and payloads to be returned to the ground

* Attachment facilities at which satellites and an Orbital Maneuvering Vehicle (OMV) will be serviced, refueled, and stored

* Unmanned spacecraft (platforms), operated or serviced from the National Space Transportation System or Space Station,

that provide power, thermal control, information management, communications and tracking, attitude control, and orbit altitude maintenance for a complement of payloads

* Support services required to process and launch the Space Station, control the Space Station and platforms, provide customer data interfaces, and train the crew

REQUIREMENTS PERTINENT TO AUTOMATION/ROBOTICS

This section contains Space Station Program requirements that bear on automation and robotics. That is, the required function is a candidate for automation, or the requirement has a significant impact on the implementation of advanced automation. All of the requirements in attachments C-2, C-3, and C-4 of the Space Station Definition and Preliminary Design RFP should be considered in the advanced automation effort. The following requirements, extracted from the RFP, are the more pertinent ones for automation and robotics.

* The initial Space Station and Space Platforms must be designed to accommodate evolution to growth configurations.

* The growth Space Station must have facilities to support the on-orbit assembly of large payload structures, including associated attachment provisions.

* The Space Station Program elements must have the ability to remain operational indefinitely through periodic inspection, maintenance, and replacement of components.

* The Space Station Program elements must be designed to facilitate system growth through use of modular design. Common hardware, software, and standard interfaces which optimize benefit to the program must be employed.

* The Space Station Program elements must be designed to accommodate the incorporation of new technology as appropriate to benefit the program.

* A phased degree of on-orbit autonomy must be provided consistent with evolving systems and operations requirements, cost, and applicable evolving technologies. Platform design will facilitate autonomous operations between scheduled servicing periods but must not preclude ground intervention.

* The Space Station Program elements and subsystems hardware and software must be designed to facilitate on-orbit and ground maintenance, inspection, and repair with maintenance performed on-orbit to the Orbital Replaceable Unit (ORU) level.

* The Space Station Program elements and subsystems hardware and software must be designed to provide for monitoring, checkout and fault diagnosis, and isolation to the ORU level without requiring removal of ORU's. For platforms, these functions must be automated, including corrective action response.

* The crew must be able to override any automatic safing or switchover capability of functional paths.

* The integrated logistics system must include an inventory management system for all Space Station Program elements and customers and must be accessible by both flight and ground systems.

It should be noted (Easter and Staehle, 1984) that no autonomous system is totally free of human supervision; autonomous systems do not replace humans in this sense. Rather, they provide much more flexibility for determining the optimal degree, nature, and location of human participation in space activities.

Figure 3 presents a general look at applications of autonomous systems by broad functional areas. Not all functional applications shown apply to every class of platform, but all would apply to multipurpose, inhabited, serviced, evolving platforms such as the Space Station.

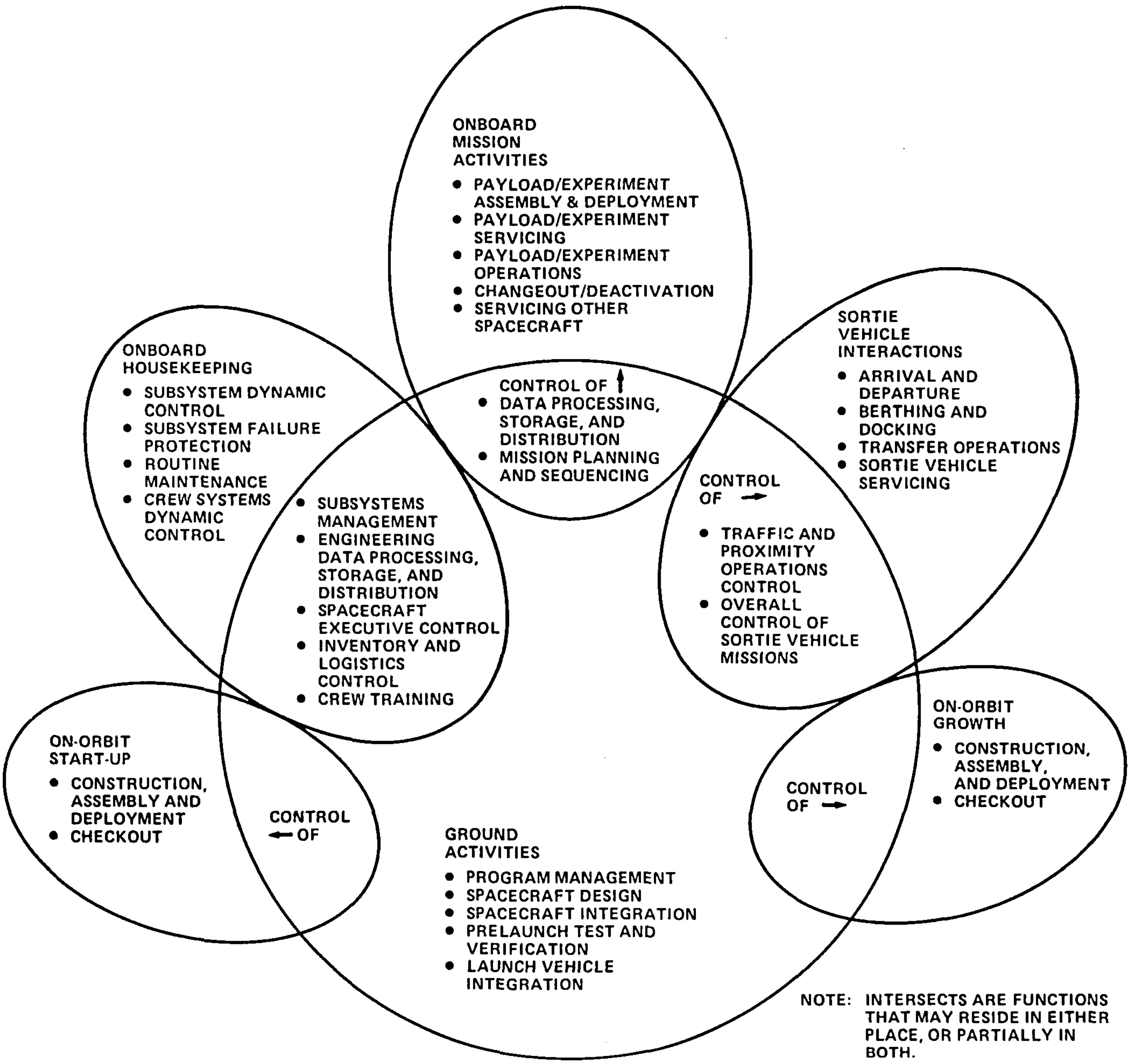


Figure 3.- Functional applications of autonomous systems (Easter and Staehle, 1984).

OPERATIONS SUMMARY

The Space Station Program will consist of flight elements and ground elements. Figure 4 illustrates the components of the Space Station Program for a mature Space Station.

The following ground rules provide a framework for the operational approach:

* The Space Station is intended to be manned unless unforeseen circumstances force evacuation.

* The Space Station System will operate in Shuttle-tended modes for material and crew resupply, for delivery of Space Station elements, and for delivery and return of payloads.

* Management of Space Station System operations (both manned and unmanned elements) will be divided between onboard and ground systems to utilize the capabilities of each most effectively.

* Communications between the ground and the Space Station System will be through the Tracking and Data Relay Satellite System (TDRSS) or its replacement system.

* Extensive preflight training will not be done for infrequent tasks (time-critical emergencies excepted.) Onboard training aids will be provided to assist in accomplishing these functions.

* Onboard flight operations will nominally be conducted 24 hours a day, 7 days a week.

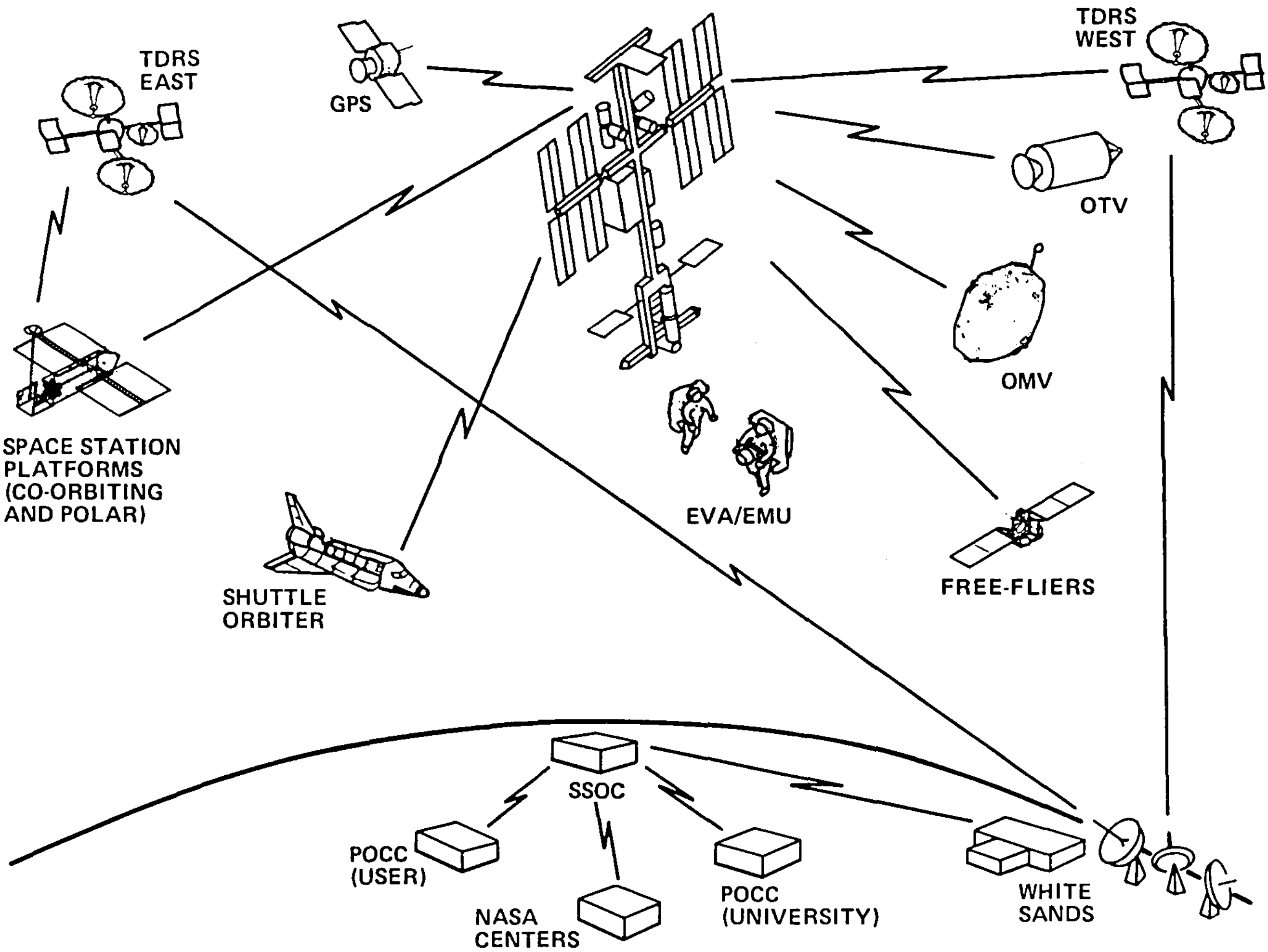


Figure 4.- Space Station environment.

The Space Station System consists of platforms, free-fliers, orbital maneuvering vehicles (OMV's), shuttle orbiters, etc., in addition to the core station. Various ones of these vehicles must be capable of being flown to or close to the Space Station (proximity operations). The station will be the operations and supply base for these vehicles, with consumables, spares, payloads, and other equipment coming to the station in a logistics module carried in the shuttle orbiter. The OMV will provide the necessary orbital maneuvers to bring free-fliers or platforms into the proximity of the station for servicing if they do not provide their own propulsion. The OMV will also provide limited in-situ platform or free-flier servicing. Manned Maneuvering Units (MMU's) will provide EVA mobility within the region surrounding the Space Station. When the station reaches full operational capability, EVA activities will be minimized by use of teleoperated devices and, eventually, fully autonomous robots.

On-Orbit Operations

A major goal for the Space Station is to minimize both crew and ground control involvement in system monitoring through onboard automation and station autonomy. This will maximize crew availability for operations support and mission activities.

Mission activities include operation and servicing of internal and externally attached experiments and payloads, laboratories, and platform-mounted experiments and payloads. Also included are servicing of free-fliers, test and deployment of payloads and upper stages, OMV operations, and, eventually, operation of large-scale construction or assembly payloads and operation of OTV's.

The complexity of the station system makes planning a critical element of station activity. In general, there are two categories of planning, near-term and long-term. Near-term consists of planning daily activities for which information is onboard. This type of planning can be accomplished onboard the station and may make considerable use of an expert system. Some examples of near-term planning activities are experiments, general housekeeping tasks, subsystem status checks, payload mission planning, and preventive maintenance. Long-term planning is that which requires the consideration and integration of numerous facts and requirements to which the flight crew may not have access or that which can be accomplished more efficiently on the ground.

Ground Support

It is believed that ground control and support of the Space Station will always be essential and that, for IOC, such support may be extensive. Ground support is required for the station itself as well as the shuttle orbiter, payloads, OMV's, and OTV's. Initial ground control and support is in the form of flight and system monitoring and assistance during the deployment, assembly, activation, checkout, and verification of each new Space Station element.

The various configurations the Space Station System will go through during its evolution will require different levels of ground control and support. Ground support will be provided for the platforms, OTV's, OMV's, and the Space Station in the form of flight and system monitoring and assistance during the assembly, activation, checkout, and verification of each new station element. Ground support will continue until confidence is achieved in the new element's operation.

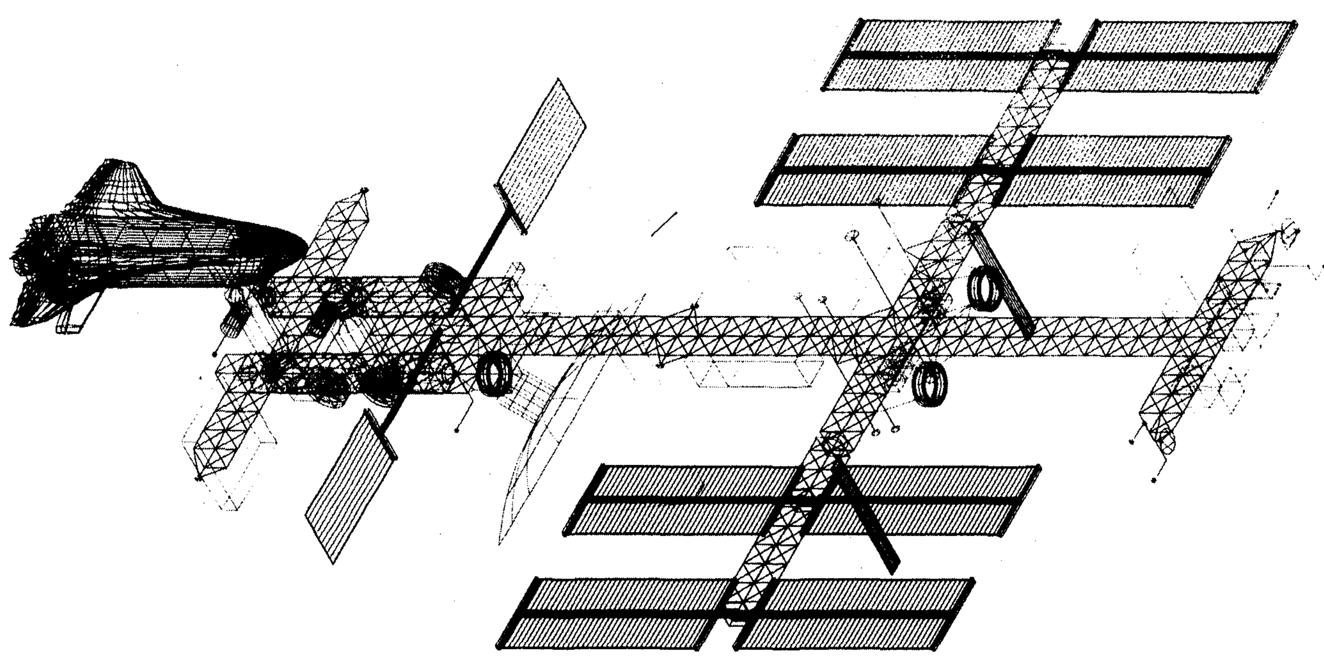
Mission planning activities for attached payloads may be done on the ground and/or by specialists onboard the Space Station. Control of attached payloads may be dictated from the ground, shared with the crew, or handled totally onboard. Payload operation and interactions with the Space Station will be conducted according to a schedule agreed upon with the customer. This schedule, or "timeline," will be maintained by the data management system (including elements both onboard and on the ground) and either the ground or onboard crew will be able to change the timeline.

The ground control facilities for the payloads (e.g., Payload Operations Control Centers) will be dedicated to the support of a specific mission. They are reconfigurable and are modified as required for each mission.

The payload ground control facilities, which are separate from the ground support facilities for the Space Station, should provide for autonomous operations consistent with those for the station itself. The payload support facilities will support payload checkout and performance monitoring, payload mission timeline planning, and a limited amount of payload data processing. Customers may use their own separate payload control facilities.

As operational confidence is achieved, ground control and support can be phased to an effective mix of onboard and ground involvement. A major application of automation technology to the Space Station is to minimize ground involvement with day-to-day station operation. The flight crew will be used for the performance of tasks where man's capabilities produce an effective alternative to automation. Autonomy and onboard automation will be emphasized as a goal to minimize ground control and crew involvement in system monitoring. Monitoring and control by either the flight crew or the ground crew will not be required for normal Space Station operations. In the growth station, automation of Space Station subsystems will free considerable crew time for support of payload operations and mission activities.

An additional benefit of station automation is to reduce the amount of crew training required. Training for crew members will be done on the ground and on-orbit. Customer training will be done primarily on the ground. The need for extensive flight crew training will be minimized, but the training must include system monitoring and maintenance; emergency procedures (including medical); housekeeping tasks; EVA, OMV, and OTV procedures; and construction and assembly procedures. There will also be specific training on individual payloads and experiments and cross-training to allow for a backup on critical tasks. Flight crew training will be as specific as possible, and training for infrequent tasks will be minimized because onboard tutorial and training aids will be provided.



Chapter 4

SPACE STATION SYSTEM DESIGN CONSIDERATIONS FOR ADVANCED AUTOMATION

This section presents Space Station Program applications for automation and robotics in a form directly related to the Space Station Reference Configuration (NASA, 1984d). After some general design considerations are introduced, including a systems approach to automation, conceptual applications of automation and robotics to selected Space Station subsystems are presented to illustrate design approaches which can be useful to follow in the Phase-B definition period. The conceptual applications represent new applications of automation and robotics in the reference configuration, and a summarized, but not exhaustive, list is included. Then considerations for Phase-B are given for automation of Space Station subsystems, operations, payloads, and experiments.

It should be noted that what is presented in this section is by no means meant to endorse, express preference for, define, or direct the efforts to any of the postulated subsystems amenable to automation and robotics. Indeed, it is not even certain that the conceptual suggestions are technically feasible - let alone practical - or that they are compatible with the exigencies associated with other Space Station Program elements. Other applications of automation and robotics in the Space Station Program may be uncovered by definition phase contractors that are far more worthy of consideration and are therefore encouraged. However, it is hoped that the suggestions presented here will stimulate thinking and that the suggestions are based, to a reasonable degree, on individual technologies which have at least been demonstrated, if not integrated into complete systems.

GENERAL DESIGN CONSIDERATIONS AND IMPLICATIONS

The potential for advanced automation on the Space Station includes almost all systems and functions. There will be an evolutionary progression toward realizing an increasingly autonomous and more productive Space Station. Therefore, initial designs must utilize as much mature automation as technologically feasible while not precluding eventual growth. The initial system design should conceptually be targeted for the mature, post-2000 Space Station and retreat from that position to IOC to ensure evolutionary growth. A primary consideration will be to achieve a design for subsystems which optimizes the human-machine mix of functions and skills. The designs should capitalize upon the strengths of both humans and machines. By approaching Space Station design in this manner, more of the long-term realizable advances in automation, intelligent systems, and robotics for the years after 2000 can be easily accommodated, once available. Furthermore, the necessary software "hooks" and hardware "scars" for the incorporation of such evolving technological advances will be in place in the initial designs to simplify the implementation at later dates.

It is critical that the initial design of the Space Station be tailored to the evolving technology of the future and not be so restricted that later system upgrades require wholesale redesign or total abandonment. Likewise, by designing the Space Station systems with the philosophy of distributed components and functions, the growth potential will be enhanced and there will be fewer single points of failure. Design for growth under such conditions is so extraordinary that some of the research to be undertaken in support of the Space Station should address such specifics as system design for growth in rapidly evolving technological environments.

Recent advances in computer technology allow increased use of artificial intelligence (AI) and robotics, which have the potential to

greatly extend Space Station operations, offering lower costs and enhanced productivity. Expert systems astronaut assistants can help to lessen dependence upon ground systems, reduce mission costs, diminish complexity as perceived by the crew, increase mission lifetime, and simplify mission versatility. A highly automated system must amalgamate the diverse capabilities of people and machines to yield an efficient system which capitalizes on the unique characteristics of each.

The Space Station must also have an initial design which allows evolution to a more automated system. In the early years it is likely that artificial intelligence-based subsystems will be used primarily in an advisory or planning capacity. As human confidence in automated systems grows and as technology advances, machines will take on more critical and independent roles. An important aspect to be considered is the degree of system autonomy necessary for Space Station effectiveness. Expert systems utilize a significant amount of expert information about a particular domain to solve problems in that domain. Planning is the determination of a pattern of actions that can be carried out to achieve a goal. The advantage of current automatic planning systems over manual techniques are speed and easy comparison of options. Future automatic planning systems will allow more complex and detailed plans to be generated quickly and without errors. When the Space Station is first launched in the early 1990's, people will play an important role in almost all human-machine systems. Monitoring will be done by computers of limited "intelligence" (e.g., fault-tolerant systems with some rule-base expertise) but under human supervision. However in the post-IOC environment, much of the decision making control will shift from ground to the Space Station, and the crew will receive intelligent advice from onboard computers.

Many of the Space Station System and subsystem functions and tasks could incorporate an increased level of intelligence to yield a significant amount of autonomy. State-of-the-art techniques for fault tolerance, fault-isolation, self diagnosis, and self repair will likely be incorporated into the IOC systems. Knowledge of how to make systems "gracefully degrade" rather than experience hard failures will certainly have an impact upon all Space Station subsystems, even those with significant levels of automation at the outset.

Another important criterion is commonality. Commonality of hardware, software, and data protocols throughout the Space Station program will be needed, especially for connectors, software models, controls, control languages, and displays. For example, it is quite probable that most Space Station subsystems will incorporate some sort of microprocessing capability as the controlling entity within each subsystem. There is a strong argument for the consideration of a common component design, at least for a standard hardware microprocessor. For subsystems experiencing a nonrecoverable failure in a controller, a simple changeout with stock microprocessors could easily be accomplished by the crew. Software for a failed controller could then be loaded into a new controller from an interfaced storage device.

The incorporation of automation and autonomy on the Space Station is related to the interplay of cost, performance, and technology readiness. While it is highly desirable to enhance the operation or automate the performance of the Station, the costs associated with achieving the enhancement as well as the readiness of the technological support must be examined in detail. An in-depth evaluation of a particular situation might show that while it is not cost effective to automate a particular function on the IOC Station, "scarring" the IOC hardware for later ease of implementation of the function should certainly be considered for providing an eventual cost savings.

Designing for Autonomy

The Space Station should accommodate alternate configurations and readily allow for both additions to and deletions from an existing mission capability. The autonomy implementation approach should have multimission applicability so that it can be

used for both manned and unmanned Space Station related needs, including diversified payloads and remotely located platforms at various orbital altitudes and inclinations. In addition, the architecture for achieving autonomy should accommodate advances in technology such that expert system and artificial intelligence techniques may be substituted for or added to current state-of-the-art computing techniques to allow increased levels of machine autonomy to be incorporated as a function of time.

All autonomous functions should be capable of being separately enabled, disabled, or updated under the supervisory control of ground controllers and/or the flight crew. This is necessary in order to ensure adequate in-flight maintenance, modification, and performance analysis. Furthermore, it allows a straightforward means for achieving executive control via ground operators, the flight crew, or automation. Such override capability by man should be tempered by the inclusion of protected command sequences in the autonomous mode. A protected command sequence should be employed in instances where the safety or operational capability of the Space Station might be seriously compromised if the sequence were interrupted during execution. The protected command sequence should warn external control sources about the dangers of sequence interruption but should still be capable of being manually overridden.

Current sensor data and autonomy-related Space Station operational status information should be maintained and made available upon request through memory readout to ground and onboard operators. This information would include the status of redundant subsystem elements, i.e., enabled, disabled, active, inactive, etc. Also, an audit trail or historical record of pertinent autonomous activities and resultant state changes should be stored and available for readout to ground controllers or flight crew members upon request. This will provide visibility to crew or ground controllers as to what has been done under autonomous control and the associated rationale for the actions. Sensor data will be required in conjunction with autonomy-related state information to interpret anomalies and evaluate operations. Key sensor data will also need to be recorded at frequent intervals. The audit trail will require correlated sensor data for interpretation. Autonomous control functions, including fault diagnosis, isolation, and recovery actions, should be accomplished with minimal disruption to normal Space Station operations for all mission phases. To accomplish this, the source of control (whether from onboard machine autonomy, the flight crew, or ground controllers) should be transparent to the Space Station user. Furthermore, the performance of autonomous activities should in no way adversely impact user-related payload integrity.

Test validation required for performing maintenance functions should be accomplished in parallel with normal Space Station operations on a noninterference basis. This would include the testing and calibration of redundant elements to maintain them in a ready state.

Any nonrecoverable fault associated with autonomous operations should result in a fail-operational and/or fail-safe mode. In the fail-operational mode, the Space Station would continue the mission in a degraded but acceptable level of operation. In the fail-safe mode, the Space Station would achieve a safe state and wait for crew or ground controller intervention. In addition, the autonomous system design should incorporate and provide multiple-failure tolerance for selected functions that are critical to successful mission operations and the safety of the crew.

Automated fault diagnosis, isolation, and recovery of many deterministic Space Station fault conditions should significantly enhance crew safety. Detection of unsafe conditions should automatically trigger warning devices such as alarms so that crew members can take appropriate safety precautions. Furthermore, the quick response times possible using machine autonomy should allow isolation and correction of many fault conditions before they can propagate and endanger the crew.

Self-test design features should be incorporated into both the hardware and software of the autonomous system to ensure proper operation even in the presence of

internal faults. Internal faults should be isolated and corrected in a manner transparent to the Space Station functions being controlled. Furthermore, software health and maintenance algorithms should be designed to perform adequate diagnostics and verification prior to issuing warnings and hardware reconfiguration commands so that the occurrences of false alarms and "trial-and-error" redundant element switching are the exception rather than the rule.

Transient errors such as transducer glitches, bit errors, etc., should be accommodated by the autonomous system design such that they are transparent to the Space Station functional operation and configuration. Normal operation would continue with no interruption or degradation in operation, and no commands for reconfiguring redundant elements would be issued.

The implementation of autonomy design features should not introduce any single-point failures in the Space Station System design or significantly deplete critical Space Station resources that would degrade reliability. Furthermore, significant increases in cycling and stress of Space Station functional elements resulting in a decrease in component and/or system reliability should not be required by an autonomy implementation. Mechanical devices having inherent wearout mechanisms (such as tape recorders, in which lifetime is based on the number of start-stop cycles) should be given special attention in this regard.

The need to modify fault diagnosis thresholds can arise either as a result of incompletely characterizing the flight environment before launch (and thus having improper thresholds) or as a result of subsequent changes in the performance of hardware after launch. There should be a rigorous examination of all fault diagnosis thresholds in the context of the expected and actual mission environment. Dynamic environmental interactions deserve particular attention.

The autonomous system design should not effect changes in a Space Station state of operation that are not reversible. This could apply to hardware spare reconfigurations where it might be desirable to return to an original configuration if all the spares become exhausted or if the autonomy-related diagnostics did not result in an acceptable corrective action.

The autonomy system design should provide protection from erroneous commands from all human or machine sources. Although the flight crew and/or ground controllers have ultimate override supervisory control over the autonomous system operations, they must be forced to send valid commands. Therefore, the autonomous system should not accept or respond to commands unless they are valid, based upon criteria established as part of the end-to-end system design of the Space Station.

Designing for Growth

Classical retrofit of the basic station, some years after initial establishment, would in most cases be prohibitively expensive. And yet a central focus of Space Station design must be to facilitate the rapid future assimilation of new automation technology into the system, particularly in the technologically volatile areas of information processing, artificial intelligence, and robotics. This conflict can be resolved using nontraditional design features up front. The following are specific recommendations for such design features:

* Design environment to accommodate commercial and off-the-shelf technology

  In order to provide a cost-effective means of avoiding obsolescence of technology utilized at IOC for the Space Station, an overriding concern is that the station and its associated facilities must be designed to accommodate terrestrial technology and procedures. The Automation and Robotics Panel document stated this very clearly - "Buy, don't rebuild!" An approach that would allow this to occur would be to design the environment for the hardware needs so that industrial-grade technology and its terrestrial specifications can be utilized in space. For example, it may be time to reexamine whether it is more cost effective to build environmental control

systems from commercially available hardware than to rebuild that same piece of hardware using space-qualified parts able to withstand the unattenuated space environment. A potential benefit from this approach would be a substantial reduction in the amount of time required for space qualification.

* Incorporate standard interfaces

A cost-effective approach that is highly recommended is the use of standard interfaces for mechanical and electrical devices, sensors, and eventually robots. For example, provide standard umbilical utility connections pervasively both exterior to and interior to the Station to accommodate the needs of both astronauts and robots. The utilities provided at each standard umbilical point must include update access to the Station's computer network, as well as to power, water, oxygen, high-pressure gas, thruster fuel, etc. Also, provide standard attach fittings at each umbilical location and through the interior and exterior of the Station, to allow automated devices to temporarily restrain themselves in six degrees of freedom.

* Design for ease of assembly and servicing

Since the degree of automation required for specific tasks is proportional to the task complexity, all aspects of the construction, servicing, and operation of Space Station elements should be kept as simple as possible. Designs of equipment need to be defined in such a way as to keep the number of steps required for assembly and servicing to a minimum. In other words, design parts keeping in mind that robots may be doing the assembly and repair in the future.

The concept of modularity should be emphasized relative to the various Space Station elements. In particular, the concept of micromodularity deserves special attention. The idea is that large objects and structures be made from smaller, standardized, interchangeable micromodular parts. This would allow great flexibility in repairing and modifying structures, and it would reduce costs and delivery times as a result of standardization and simplification of logistic control. Another advantage, which is the theme of this report, is that it lends itself quite readily to automation, first by remote control and teleoperation and later perhaps by artificial intelligence methods as they evolve.

* Design for ease of identification and accessability

Provide highly visible navigation markings and upgradable beacon systems (both internal and external to the Space Station) in such a way that astronauts and automated devices can easily determine their location and orientation relative to the station to minimize the cost of automated vision systems. These markings should be dual human/machine readable, such as standard OCR fonts or normal text plus standard bar codes or color coded insignia, etc. Use of special markings would also allow even currently available computer systems to keep track of all items and connection points. This would be extremely useful when new devices become available.

* Design for autonomy of routine deterministic operations

Routine functions involving preplanned operations (sequencing, mode changes, configuration changes, etc.), management of deterministic a priori-defined fault conditions, and required maintenance of onboard resources should be performed autonomously in order to reduce the workload demand on the flight crew and/or ground controllers. Man's role in the performance of these functions would be primarily monitoring and supervision. This will allow more efficient application of human resources. However, the implementation of autonomous design features should provide for self-checking operations with performance monitoring so as not to add appreciably to the time required for in-flight checkout, initialization, and maintenance of the

Space Station System. Otherwise, the workload reduction realized from autonomy could be superficial.

Reducing man's workload on routine monitoring and supervisory tasks allows him to devote himself to tasks requiring greater sophistication. Autonomous monitoring and diagnostic functions should enable faults to be diagnosed earlier and propagation of the effects of faults to be reduced. Autonomous decision processes should enable more rapid and efficient responses to stimuli.

* Design an evolutionary computer system architecture

  Electronics evolution is a driver for computer technology. This is currently a rapidly evolving technology. As mentioned in the introduction, this area probably represents the greatest challenge when it comes to designing a computer architecture for IOC that is capable of evolutionary growth. The evolution of the computer system directly affects the evolution of operating systems, algorithms, computer graphics, computer simulations and artificial intelligence. Hence, care must be taken in the initial computer system design to ensure that smooth transitions between initial and evolutionary systems occur.

  The architecture must be able to accommodate advances in technology such that artificial intelligence techniques, e.g., expert systems, may be substituted for computing techniques utilized in the IOC design. There are three concepts worthy of note - central computer, hierarchy, and distributed. Each has its advantages and disadvantages, which are briefly discussed next.

  A centralized computer system uses a single central computer and some limiting processing ability in peripheral devices. Until recently, this has been the dominant design in industrial use.

  A hierarchy of computers is a development of the central computer design concept. There is something like a central computer at the top of the hierarchy. This computer is interfaced to second level computers, these to third level and so on. Generally, computers at the same level do not communicate with each other or to more than one computer at a higher level. The interconnections are thus tree-like, and the system is isomorphic to a logical partitioning of the algorithm to be executed by the top computer. As an example, the top computer may deal in terms of pilot commands, engine condition, and air frame condition, having each of these abstracted by a subordinate computer.

  A distributed approach does not include a central computer, nor does it restrict communication as does the hierarchical approach. Any computer in this approach can communicate with any other computer. This overcomes the rigidity of the hierarchical approach and permits free addition of units to the system, within engineering constraints. It increases the independence of the individual subsystems while requiring a simpler software executive for the central processor to schedule the largely autonomous subsystems. Also, this approach provides higher performance since the subsystem unique processing requirements may be performed simultaneously using parallel processors. It has the disadvantage of not modeling formal logic; it models a tangled hierarchy, making correctness and consistency checks difficult and intermittent error resolution formidable.

  None of these are really well suited to an evolutionary approach. The central computer is easier to replace than to modify, but replacing it would shut down the Space Station. A hierarchy would allow technology transparent interfaces at each mode, if properly designed. It would, however, not gracefully accept changes of station concept. A distributed approach has similar, although less severe, problems with complexity and change. For example, addition of a new unit can require that all existing units be notified of the name and abilities of the new unit and possibly how

to use its abilities as well. This chore, together with a general lack of amenability to paper verification, may make modification of distributed systems difficult.

A candidate concept for consideration that would perhaps reduce the severity of the problems mentioned above is a hybrid system between the hierarchical and distributed system approaches. This system would employ distribution of the subsystem unique data handling and control functions but centralization of the system-level executive control functions.

* Incorporate CAD/CAE for accommodating artificial intelligence and robotics technology

Use of expert systems in the Space Station program has been identified as one very real application of artificial intelligence research. In conjunction with expert system development, considerable attention should be given to the use of computer aided design and computer aided engineering. At the very earliest time, design the Station-related CAD/CAE effort to couple and facilitate supply of information to expert systems. This couple is critical because so many expected elements of the Space Station are "model number one, serial number one." That is, there is no knowledge base to draw from except as created by the individual designers for each subsystem. It is essential to capture not only maintenance ideas from the designers but also reasons for such decisions. In addition, means must be provided for including later experience in the knowledge base. To allow the TMIS to develop without early couple to expert systems design activities may forever preclude use of this viable AI resource in many critical areas. Once lost, design thought processes can never be completely reconstructed. These considerations should also be extended beyond the design phase into configuration, inventory, and change-control during operations.

Designing for Ease of Communication and Cooperation With Intelligent Systems

In early stages of Space Station evolution, including IOC, artificial intelligence will be represented in elementary forms. The reasoning and intelligent control of systems by machines will be preceded by a strong reliance on man as decision maker. Automation and robotics will necessarily, and most productively, be applied in expanding and enhancing man's capabilities. Man will necessarily be more than ever "built into the loop." Thus, an apparent contradiction in design paths exists. Man will be provided more and more with subsystems to improve his productivity and tailored to his organic attributes. Artificial intelligence research, on the other hand, has as its aim the sharing and eventual supplanting of man as decision maker. Artificial intelligence currently resides in standard computers, or extensions of those computers, not unlike machines that will comprise the Space Station Data Management System. Computers serve as hosts for artificial intelligence for lack of anything better, not because computers, as currently understood, are best designed to implement the results of this research. As a consequence, it is unlikely that the Data Management System will either be amenable to early sizing to accommodate eventual artificial intelligence (excluding expert systems) or adaptable to the actual computational hardware which will eventually carry AI using standard or classical methods.

An approach which may permit sensible sizing of the DMS and graceful transition into the era of artificial intelligence might be by means of workstation technology (figure 5). The workstation could serve as the gateway for both man and artificial intelligence. Thus, design of the workstation must, at the outset, be more considered than the already difficult job of providing effective man/machine interface. In addition, this approach places restrictions on the DMS architecture in that direct access to required data and control be accessible at any workstation. A characteristic of this insertion approach is the gradual disconnection of the man as "do-er" in favor of man as manager.

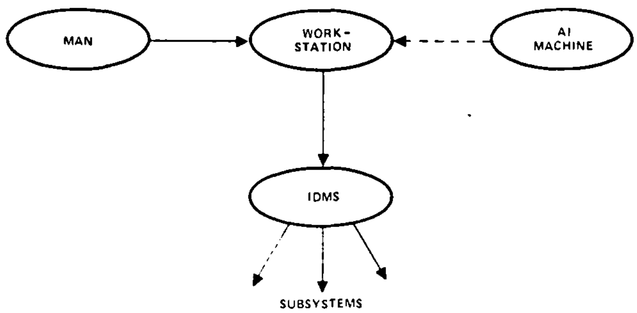


Figure 5.- Concept for growth into artificial intelligence via workstation as a gateway.

Technologies to be considered for workstations would be speech recognition and understanding, computer-aided vision (not necessarily computer vision), natural language computer input, heads-up display, data (information) fusion, advanced controller (joystick) input, three-dimensional (stereo) presentation, computer-generated images, reconfigurable control panels, and last, but most importantly, a standard interface for insertion of AI systems.

Left to happenstance and individual heuristic skills in the past, formal analysis and synthesis of man/machine interaction has become an important aspect of psychology and engineering work. From recent studies have come improved and more standardized automobile controls and instrument panels; vastly improved aircraft displays and controls; and computer architectures and workstations which greatly enhance the efficiency and effectiveness of software generation. Particularly in the case of the aircraft cockpit, understanding has been acquired relative to the placement of switches and displays to accommodate human anatomical constraints and mental context. As a result of this work, many previous causes of death have been eliminated.

The way in which humans interact with computers can have a profound effect on the productivity of software engineering. The Department of Defense has recognized this by creating a man/machine interface interest area under the Human Engineering thrust of the potentially $200 million per year Software Technology for Adaptable Reliable System (START) program. Likewise, it is funding the creation of user-friendly software through the development of its standard computer language, Ada. Both Ada and ATC UNIX operating system are examples of computing enhancements having human interfaces which are consistent across broad classes of machines and applications.

The Space Station, as well as other large and complicated systems such as nuclear power plants, will need computer-automated systems of control effectively interfaced to human operators functioning as high-level monitors and supervisors. The concept of supervisory control should be incorporated in the Space Station at increasingly higher levels from the highest available at IOC. Essentially, supervisory control will permit the human operator to input to the system high-level goals, after which the system will then devise a plan of implementation and set that plan in motion. The system also will be responsible for making available to the human, upon request, details of its plan and the logic used to generate the plan, as well as system status in goal accomplishment. The system should be designed to permit the human to intervene and assume control of any aspect of system functioning at any time and at any level. Thus, humans themselves will be able to replace directly the inappropriately functioning failed system parts at any time required. Under supervisory control, the system will perform diagnostics of its subsystems solely or optionally interactively with the human operator.

Although at the highest and most creative levels of planning, the human must become directly involved, the machine will even at this level handle most of the plan subparts which require such elementary processing as plan element sequencing to avoid conflicting constraints. Thus, the human can specify major plan segments which the machine will then plan in detail. At earlier stages of supervisory control, all planning may be done by humans who will request the system to merge in a specific sequence elemental, predefined sets or packets of actions; i.e., an action packet might be "grasp the beam" or another might be "translate the beam to x, y, z."

The implementation of supervisory control will require the development of displays and controls which facilitate human/machine communication, especially interfaces which permit the system judgment in presenting the human as highly processed and condensed information as will meet his needs or satisfy his requests. Thus, displays should permit the presentation of more-or-less detailed information as is appropriate. Voice communication (both input and output) should be researched and developed to very high levels of sophistication. Touch panel displays can be programmed to provide a very efficient interface, because they can present more readily grasped pictorial information while at the same time providing it in a hierarchically decomposable form. Thus, the operator could be presented a high-level block diagram of, for instance, the Space Station electrical power system. By touching a subblock of it, the operator could bring to full screen a block diagram of the touched subsystem. The touch selection could then be used incrementally to take the operator to the lowest required level of detail.

Although automated equipment soon will, for the range of functions for which it was designed, have capabilities similar to those of humans doing the same job, there will remain aspects of the job at which the machine is superior and others at which the human is superior. These advantages and disadvantages should be identified, and as policy a division of labor be made between humans and machines accordingly. For instance, humans are extremely good at recognition at which machines have great difficulty. On the other hand, humans have great difficulty precisely locating objects in space. Automated machines can be designed with sensors to do this quickly and well. Thus, interfaces need to be designed which permit humans and machines to readily request and supply complementary information of this type. Through these interfaces, then, the machine may ask the human, "What is the object I have zoomed in on on monitor 5?" Likewise, the human may ask, "How close is the antenna in the upper right corner of monitor 8 to thrust port 21 C?"

Development of more effective man/machine interfaces requires the continued development of powerful computers coupled to fast, large storage devices such as those which allow vocal man/machine communications. Artificial intelligence techniques along with knowledge-based systems coupled to large data bases will relegate human interaction to higher and higher levels as machines take over more and more of the detailed control of devices.

Complex digital computers allow displays which may be dynamically reconfigured to best present data to humans. Information indicating dangerous conditions may be presented in ways that enable rapid interpretation. Similarly, keyboards and other electromechanical devices will facilitate increasingly rapid control of machines. The effective use of these capabilities requires knowledge of how a human mind uses the data presented to it. The effective response requires knowledge about how humans can physically react. With such knowledge, displays and control devices can be optimized.

It is interesting to speculate about the future. One day, computers might be able to read the human mind and react to what is being thought. Even today, simple commands can be relayed by thought to machines. In the future, one will be able to have a computer supply answers and information without our conscious direction. On the positive side, this will free humans from the necessity of long training to coordinate visual stimulation and motor response. On the negative side, the computer could be used to introduce unwanted or unsolicited thought.

SOME POSSIBLE AUTOMATION AND ROBOTICS APPLICATIONS TO SUBSYSTEMS IN THE REFERENCE CONFIGURATION

In order to provide the Phase-B contractors with points for departure, it is the purpose of this section to suggest some of the ways that automation and robotics might be applied to the Space Station. Whereas the specific suggested applications are by no means meant to be exhaustive or in any way definitive, they do represent an approach for generating concepts and for identifying the specific

automation and robotics technologies that could be brought to bear. The degree of maturity of specific automation and robotics technologies involved can then be assessed to determine feasibility for IOC or Evolutionary Station.

Since Phase-B has not yet begun, the only definition of the Space Station available is the reference configuration, defined by the Space Station Program Office during the summer of 1984. It is intended to be used as a starting point for the definition studies. The Reference Configuration has implications for automation and robotics which are described in this section. While the final configuration may differ considerably from the reference, it is likely that many of the concepts embodied therein will be retained. As a result, the following discussion of potential automation and robotics applications on the Space Station can be expected to provide examples of the differences between current technology and a reference minimum scope planned for the Space Station.

Electrical Power

The power system for the IOC Space Station may be either a photovoltaic or a solar dynamic system (NASA, 1984b; NASA, 1984c; and Fordyce & Schwartz, 1984). For a photovoltaic system, either regenerative fuel cells or batteries may be used for energy storage. A solar dynamic system can utilize either a Brayton or Rankine cycle energy conversion system. Additional power will be required for the growth Station. Both solar dynamic and nuclear power systems are especially attractive candidates for the growth Station because of low areas and high efficiencies. All of these candidate power systems are extremely compatible with autonomous robotic modes of operation, maintenance, and repair.

The long-term generation of power in space, regardless of the system, will require status monitoring and both preventive and repair maintenance. The type and frequency of maintenance functions will vary between the various systems (and their component parts) since each system will be subject to its own peculiar performance degradation and failure modes. Solar photovoltaic degradation can occur in many ways - micrometeroid impact damage, atomic oxygen attack, long term degradation because of space radiation effects, and possible surface degradation because of rocket plume impingement. In the case of storage systems, regenerative fuel cells are subject to different failure modes than rechargeable batteries. Solar thermal dynamic systems may also experience concentrator performance degradation because of the above phenomena (though probably to a lesser extent) and/or possible mechanical-electrical malfunctions in the dynamic machinery. Other problem areas include the thermal loops and the thermal storage medium. Nuclear systems with dynamic energy conversion systems could encounter the same failure modes in addition to reactor anomalies. Both the solar dynamic and the nuclear systems require large heat rejection radiator surfaces, which are subject to a number of possible failure modes.

Autonomous operation and robotics technologies are directly applicable to the status monitoring, controlling, and maintenance/repairing of these power systems. Automation and robotic techniques will reduce astronaut time for the operation and maintenance of these onboard systems. For systems such as solar dynamic and nuclear (with high-temperature and high-pressure hazardous environments in addition to the radiation environment of the nuclear systems), automation and robotics techniques will contribute to astronaut safety.

The required functions for the Space Station power system which will benefit greatly from the application of autonomy and robotics techniques are

* System monitoring, including state estimation, trend identification, and fault diagnosis
* System control/load management
* Automated maintenance
  - Inspection
  - Repair and replacement scheduling

The power system on the Space Station will be, in many respects, analogous to a terrestrial utility system. It must serve its customers (Station power users) just as a utility must serve its customers. Therefore, the operating practices of terrestrial power-producing utilities are in many respects, directly adaptable to "optimize" the operation of the Space Station power system. Fundamental concepts such as power plant dispatch, power system state estimation, and load management have been employed by utilities for many years. They are directly applicable to autonomous operation of the Space Station power system and are reflected in the automation and robotics technologies which will be adapted to the Space Station power system.

The above functions will be carried out at the component part, subsystem, and system levels, as required. The actual requirements will be determined by a detailed analysis of the power system.

In order to realize the benefits of automation and robotics technologies, the power system should incorporate into its design the features necessary to permit the above functions to be performed. Built-in test point sensors and instruments should be provided for data acquisition in order to accomplish system monitoring and statusing and state estimation of the system. For the repair, replacement, and maintenance aspects, the total system should be designed with a high level of modularity.

Monitoring - state estimation techniques. System monitoring will be accomplished by a combination of mechanical/optical inspections and electrical monitoring of built-in sensors to collect data on the status of the individual component parts of the system. The data will be stored in the memory banks of onboard computers. These data are then analyzed by means of a "state estimation" program which operates on the data in a way so that it can be used as an indicator of what is actually occurring in the power system (e.g., the state of the system).

For a photovoltaic system, the replaceable element may be an array section. Each array section may be provided with visual-electronic identification, including wired-in test points. The state estimation data banks might contain operating data on the individual arrays, including efficiencies, outputs, expected degradation with respect to time, etc. Many possibilities exist for array modularity. Instead of array sections, an entire foldable array assembly such as an OAST-1 or SEPS array (Lockheed array) may be the optimum level of modularity. A detailed system analysis is required to determine the optimum design.

For the energy storage unit (either a regenerative fuel cell or secondary batteries), the same logic applies. Data on the individual units can be stored for comparison with sensor data. The fuel cell or battery system might be designed at the orbital replacement unit of modularity. Within each unit, as with sections of a photovoltaic array, repair and/or replacement is not anticipated.

For the solar thermal dynamic system, the performance of the concentrator may be monitored by surface sensing devices, possibly laser beam instruments. By using these sensors, the degradation of surface coating optical properties, surface distortions, etc., can be determined. The performance of the entire active concentrator surface can be evaluated. The level of modularity might be a petal section or some other structural division. The status of the thermal medium and heat transport loops may be monitored at critical points by sensing the pressures, temperatures, and fluid flow rates. The dynamic machinery will also be fitted with appropriate sensors where electrical measurements (voltages, currents, and frequency) can also be monitored.

For the nuclear system, much of the thermodynamic-mechanical-electrical monitoring is identical to the solar thermal dynamic system. In addition, the reactor must be instrumented. The radiation environment must also be continually monitored to ensure the safety of the crew.

The power distribution system follows much the same pattern. Its status can be

monitored electrically with sensors at selected points.

Trend identification. The status or "state" of the power system or any of its component parts will be determined by the state estimation program resident in the onboard computer. Comparing the estimated state with the expected state will give an indication of the system status. By maintaining a record of the estimated states, performance trends can be established for any level desired (system, component, etc.). Maintaining a time history of the performance allows trends to be established for predicting when component operations may become unacceptable and/or require maintenance.

Fault diagnosis. The state estimation program - by virtue of the data it compiles to determine system, component, or part status - can also be used in a fault-diagnosis mode. When the performance is degraded beyond a certain level, the state estimation program can identify the component part. Upon identification of the fault, the monitoring system can automatically switch to a mode for collecting additional data on the faulty component from lower-level sensors (which are provided but not normally recorded during nominal operation).

System control/load management. The Space Station power system might incorporate some degree of redundancy among its components and provide some excess capacity for output. For the solar-based systems in particular, excess photovoltaic or concentrator capacity must be provided in order to accommodate some performance degradation with time.

The information resulting from the state estimation system may be input to an "expert system controller." In nominal operation, the controller should maintain normal load management control. In those situations where performance degradations arise, the controller should try to maintain constant bus output by switching redundant components or by utilizing excess capacity, if available. If excess capacity is not available or if a serious power system failure were to occur (loss of one entire solar wing, for example), the expert system controller could carry out load management functions by rescheduling lower priority loads according to a predetermined scheme which has been based on estimates of future system performance.

For the case in which the energy storage system consists of high-performance secondary batteries, the controller may perform an optimum system charging function. Data on the individual cells might be stored in the onboard computer memory banks. Trend data on individual cell performance can be maintained and used to determine the optimum system charging profile to maximize the energy stored per charging cycle.

In conjunction with the load management function, an expert systems controller can be used to determine optimized repair/replacement schedules. The operation of an expert system controller can be much the same for either photovoltaic, solar thermal dynamic, or nuclear systems.

For heat-based power systems such as solar thermal dynamic or nuclear, waste heat utilization from these systems may offer significant advantages for reducing power, system mass, and/or electrical demands. The actual gains to be realized might be a function of the particular heat-using applications under consideration. Significant applications of autonomous control are possible here. An expert system controller, in its function as load manager, could determine waste heat availability and quality for (optimum) dispatch to the various using processes.

Another integration possibility exists if a regenerative fuel cell were used as storage for the photovoltaic power system. The outputs of a regenerative fuel cell, used in a regeneration mode (as an electrolysis unit), are oxygen and hydrogen. Cabin oxygen, needed for breathing, could be supplied by the electrolyzer unit if it is properly sized. An expert system controller could be used to determine the optimum mode of operation of a regenerative fuel cell employed as both an energy storage system and a cabin oxygen supplier.

Automated maintenance. Initially on the Space Station, EVA's will play a dominant role for maintenance, but teleoperations will be used occasionally. On the growth Station, automated teleoperator and mobile robotic functions will be used.

To ensure the evolvability of the Space Station, provisions for autonomous-robotics operation must be made in the IOC design. For the power system, the level of unit replacement, or modularity, must be a part of the system design. Connects and disconnects for all functions (electrical, hydraulic, and pneumatic) must be incorporated into the design at the replacement-module level. Module accessibility is also a prime design consideration.

Inspection. Upon detection of a malfunction, it may be necessary to employ visual inspections to determine causes and/or the extent of damages. This may be especially important for those components subjected to external influences such as solar panels, the solar concentrator, and radiator surfaces. In the early stages of the Space Station, astronaut EVA's may dominate, but fixed television or teleoperated television may also play an important role. For the more hazardous areas of the nuclear or solar thermal dynamic systems (which may be beyond fixed or teleoperated television range), automated mobile robots will be necessary.

For those components with uniform surfaces, such as solar cell wings, radiator assemblies, and solar concentrators, optical scanning devices could be designed as integral parts of these components for automatically scanning these surfaces. These would be mounted on carriages in order to determine the condition of the surface. The information obtained would be used by the "state estimation-expert system controller" to verify status, estimate performance trends, control related functions such as solar orientation and load management, and prepare repair and maintenance plans. Automated inspections of other components are also possible.

Repair and replacement. Like the inspection function, the autonomous robotic repair and replacement capability must be designed into the Space Station. Modularity, connectors, and access must be considered in the Station design.

For very hazardous situations, such as high-temperature or high-radiation environments, the robotic or remote operator system will greatly increase astronaut safety. However, the remote operator must be capable of withstanding these extreme environments. Also, provisions must be made to store the replaced units safely.

Operations. Automation and robotics technologies offer significant benefits to Space Station operations. Employing these technologies will result in significant reductions in astronaut time for operating, monitoring status, and maintaining the power generation system. Also, improved operations will result from using expert system controllers in evaluating options, schedules, etc., which are beyond the reasonable capability of an astronaut.

To support Space Station implementation of advanced automation and robotics technologies, the following technical disciplines have been identified:

* Teleoperations and robotics
* Pattern recognition techniques
* Optical inspection techniques
* System modularization design
* Advanced data display concepts
* Sensors and instrumentation
* Advanced, high-speed computers
* Expert systems logic development
* Integrated Station design concepts

The power system interacts with all other systems of the Space Station. Degraded or anomalous performance of the electrical power system will affect the overall operation of the Space Station. Highly complex interactions, requiring the analysis of a vast

amount of data in a short period of time, are required to maintain optimum control of the Space Station. Expert systems and artificial intelligence logics will be used to perform these functions. Automation and robotic inspection and repair techniques are also required in some cases necessary for astronaut safety.

No impediments to incorporating automation and robotics technologies into the Space Station power subsystem are seen to exist. The process is expected to be evolutionary. In designing the Space Station electrical power system, consideration must be given to future autonomy and robotics requirements.

Guidance, Navigation, and Control

The Guidance, Navigation, and Control (GN&C) subsystem of the Space Station has many responsibilities, functions, and interfaces. An example of automation and robotics being applied to traffic control management, which will be addressed later, is an important function of the GN&C subsystem. This section presents some applications of automation in the other major subsystem function, attitude control. The attitude control function includes the attitude control of the Space Station itself, orbital maintenance, solar pointing, and experiment stability. It is planned that the Station be flown in a torque-equilibrium attitude such that momentum contributions from aerodynamic torque, gravity gradients, etc., total to zero for each orbit. Attitude control can be maintained by a momentum torquing capability of modest size. However, the flexibility of the Station structure may introduce dynamic control interactions which are more severe than experienced with any previous spacecraft attitude control system.

The Space Station Reference Configuration Document (NASA, 1984d) indicates the application of distributed computers to satisfy the many functional requirements; i. e., automation is already required by the nature of the functions. It is seen that the application of expert systems might be considered for identifying trends and for warning personnel of possible impending attitude control problems. The referenced guidance and control computer interfaces with many subsystems, such as star trackers, torquers, Control Moment Gyros (CMG's), actuators, and the like. It is very likely that improvements in many of these subsystems will evolve. For example, a "smart" star tracker may be developed that is capable of determining guide stars and navigational parameters, conducting self-calibration and making decisions about the information that normally would be processed by the guidance and control computer. Consequently, it is important that the design of these interfaces consider such developments and provide accommodating interfaces. Further, the subsystems should be designed for possible robotic replacement or retrieval and repair inside a laboratory module.

Operations of platforms, free-fliers, OMV, OTV, and the Shuttle in and around the Space Station will require a Space Traffic Control capability. Air traffic control (ATC) technologies and operations methods offer a large body of knowledge from which to draw. Taken together, techniques for RPV's and ATC offer a method for automating formation flying around the Space Station. The synthesis task, however, is further complicated by the requirement that orbital mechanics algorithms be added to the flight path control software for static station keeping and movement in and around the extent of the Space Station. An important element in a GN&C system for the Space Station is effective location and velocity information in the 8-kilometer sphere and forward and aft 30-degree cones called Space Station "area of influence" (see NASA, 1984d, p. 419, "Traffic Control and Proximity Operations"). Sensor systems capable of performing this function may have to be developed since Global Positioning System accuracy is insufficient to permit close-in maneuvers. Potential sensor approaches or techniques might be:

* Submillimeter phased-array radar
* Scanning CO-2 or Nd:YAG coherent or incoherent radars
* Collection of CCD TV cameras mounted around the Space Station with automatic

target identification either through beacons that are optically coded on the free-fliers or simple template matching computer vision recognition.

Some of the automation and robotics technologies involved with the guidance, navigation, and control subsystem are as follow:

* Sensing and perception (target identification)
  - Miniature radars
  - Laser radars
  - CCD TV cameras and coded optical beacons
* Advanced computers
  - RPV control system
  - ATC computer
  - Orbital mechanics algorithms for trajectories, etc.

For the Space Station IOC the identified technology development requirements include the formulation of orbital trajectory algorithms for near-Station EVA's. For FOC the technology development requirements include a collision avoidance sensory capability and an accurate trajectory planning and control capability. IOC hardware "scars" identified include the use of GN&C computers or computer networks which have been sized to accommodate the RPV and ATC orbital mechanics software plus I/O ports sufficient to control multiple free-fliers. Sensory systems will require the ability to add additional sensors to the Station elements as they grow. This will require the addition of ports with connections to power and data networks.

Communications and Tracking System

The communications and tracking system for the Space Station is quite complex because of the many communication users which must be simultaneously addressed (EMU, free-flier, OTV, OMV, platforms, Orbiters and TDRSS's) from the Space Station. The Space Station Reference Configuration Document (NASA, 1984d) describes the need for as many as 28 antennas for communication and tracking functions. The complexity of allocating usage of these antennas, scheduling, setting data rates for the associated modulators, and controlling the actual pointing for those that require pointing requires computer control that borders on the edge of expert systems, because the software will control the communication links by a priority scheme. Robotics can play a role in the replacement and repair of components, including the antennas themselves, because of their external locations (impact absorbers and convenient tiedowns), and the electronic packages involved in the communication and tracking system (such as the low-noise front ends, diplexers, switching networks, and pointing servos). This means that much thought must go into the design of subsystems, antennas, etc., to allow future use of robots to replace faulty components. Modularity is seen as the key to this requirement.

Communication with the ground via TDRSS may employ one or more movable dish antennas. As the Space Station moves in orbit, a switchover period from one TDRSS to another occurs. Whereas this may be momentary, high data rate sources will require scheduling and intermediate data storage in order to maintain continuity. Automation technology can be brought to bear when used in conjunction with advanced high-speed bulk data memory systems (in the DMS). The communications control subsystem may contain a scheduler that is fed information by the DMS regarding blackout occurrence and data transmission requirements. The communication control subsystem may generate a request for bulk storage during blackout, determine the amount of data to be stored, and restore the required effective transmission rate. If the data rate available is insufficient to compensate for the communication interruption, the communication controller could request rescheduling of tasks in the DMS master scheduler to yield no loss of data or perform some other corrective action. The addition of Multibeam Phased Array Antennas (MBPA's)

could permit much faster switching to reduce interruption time. This would be expected as an evolutionary capability and could result in a single antenna for TDRSS communication. However, use of an MBPA might allow a multiple-beam antenna application and could benefit from a high-speed bulk memory scheduler operating in an effective multiplexer mode. The data rate for communication links might be increased to give constant effective Station-to-ground communication rates.

There are several automation and robotic technologies involved which have been identified and are listed as follows:

* Smart communication subsystem
* High-speed dynamic scheduler
* Advanced high-speed high-volume data storage in DMS or communication subsystem controller

One of the identified technological development requirements is the need for the storage of massive amounts of data. Two specific areas which have been identified for consideration on the IOC Space Station are

* Communication controller capable of intelligent interaction with DMS
* Provision for high-speed bulk data storage peripheral in communication controller or DMS

One identified critical interrelation with other Space Station subsystems for the tracking and communications subsystem is to provide a high-priority interface with the DMS during subsystem design.

Automation and robotics technologies which have been identified as being applicable to the communication and tracking subsystem include sensing and perception (including advanced displays to relate status, routing, and near-term schedules and computer vision for the detection of communication subsystem degradations or antenna blockage). Teleoperators and robotics are seen to have potential for the communications and tracking subsystem for repair and replacement of failed components. Advanced computers show promise for automated control of communication networks, data rates, data compression techniques, data link allocations, override control, and determination of data redundancy. Also, an advanced computer with a knowledge-based program could keep track of antenna pointing for establishing links. An expert planning system would provide a tremendous tool for the communication and tracking subsystem as a data transfer scheduler and controller. Technology developments are required in the areas of computer vision; robotics, for fault repair and replacement; expert systems, to automate link scheduling and control; displays, for presenting status to the crew; and speech recognition and synthesis, to achieve hands-free man/machine interface capability. IOC to FOC growth "scarring" should include component designs which would lend themselves to robotic repair, adequate sizing of computational facilities to allow for growth of expert planning and management, and design of antennas for high data rates at high frequencies.

The above considers the communications function of C&T. The other major function, tracking, is considered below.

The operations of the Orbiter, OMV, MRMS, MMU, EMU, and EVA will result in frequent mating of free-flying or unattached craft and berthing of various cargo with the Space Station. Two major subsets are indicated. The first includes those crafts or modules possessed of self-contained propulsion systems which are compatible with maneuvers in and around the Space Station (e.g., terminal docking Orbiter). The second includes those crafts or modules which are either unpowered or do not have fine control propulsion systems.

Powered craft may either be manned, controlled from the ground (perhaps via TDRSS), or controlled from the Space Station itself. Those vehicles controlled independently of the Space Station represent the most difficult to which to add automation in tracking and docking. The most beneficial level of automation applicable would be in a man-enhancing sense. That is, automation of subsystem tracking should be considered to

yield information derived from advanced docking sensors (also compatible with closed-loop control), which provide an integrated simple display of target location approach rate, position error, warnings, etc., for simplifying the maneuvering procedures required of the pilot. Ultimately, an upgrade of the powered free-flier to closed-loop GN&C may be required in order to minimize docking shocks to delicate user equipment and/or to experiments and the Space Station structure.

Unpowered objects may likewise require tracking and docking, yet additionally require the function of berthing. The latter may be accomplished by the Space Station RMS devices but may also be effected by another device, such as the Orbiter RMS. Here automation technologies at the subsystem level (mentioned above) can be brought to full use by closing the loop from tracking sensors (and berthing and latching sensors) through the RMS control system. The information extracted from sensors in and around the docking and berthing area would not only be displayed but also be routed to the control system. Man could then perform the role as a monitor of events and intercede only if required by anomalous conditions. The key to providing automation in tracking, berthing, and docking lies in sensors capable of determining x, y, z, range, range rate (velocity), and orientation with respect to the desired contact location. Currently, only simple aids are available on the STS. Conventional RF radar is impractical at close range because of multipath interference, low angular resolution, etc. However, various new techniques such as millimeter/submillimeter radars may be applicable, while laser radars (coherent and incoherent) in various configurations have demonstrated good accuracy (1.0-millimeter resolution in 10-centimeter to 10-meter range) with the added advantage of high angular resolution. Orientation determination remains an area to be developed. Current concepts using retroreflectors at specified locations amenable to unambiguous orientation determination imply a considerable degree of cooperativeness in the target as well as human intervention to find and identify the target and set coarse target orientation. More productive techniques, which still require some human intervention, could be based on computer-stored sets of reference diagrams of the expected targets in line-image format. The stored information could be compared, in real time, with a line-extracted image of the target to yield orientation and distance. Computer vision systems are currently capable of extracting such line images, and a considerable capability to perform this task may already exist. A critical issue in this area is high-speed, near-real-time line-image extraction and comparison.

The automation and robotics technologies involved are sensing and perception (including advanced displays, proximity and pressure sensors, computer vision, and integrated sensor processors), teleoperators and robotics (including closed-loop robotic arms and closed loop GN&C systems), and advanced computers (including coordinate processors, optical disk technology and two-dimensional image correlators). Improvements in technology are required in the fields of extended computer vision, miniature high-power solid state lasers for extended target range and an uncooperative target acquisition capability. IOC to FOC growth "scars" include the provision at docking and berthing areas for CCD size TV cameras and miniature laser radar transmitters. Identified "hooks" include a control software and hardware environment which is capable of operating with direct sensor input instead of low-speed human joystick input. One critical interrelation of the communication and tracking subsystem with other Space Station functions applies to the Orbiter. An upgrade of avionics systems to provide closed-loop control of RCS is required for ultimate performance. No other critical interrelations are seen to exist.

Information and Data Management

The evolutionary growth of the Space Station and the short-term uncertainty of that growth demands a data management system (DMS) that is itself capable of evolving. Electronics systems should be added (or deleted) to meet changing Space Station requirements and to accommodate continuing advances in electronics, automation, and robotic technologies. One data system architecture which is thought to be capable of

the evolutionary growth anticipated for the Space Station DMS is based upon local area networks (LAN's). This network should allow data system alterations to take place with a minimum amount of disruption to the normal operation of the DMS. The DMS LAN design should allow for the expansion of network capacity and performance to meet the projected requirements of the DMS if a major system overhaul is to be avoided as the Space Station approaches FOC.

A degree of fault tolerance is achieved in a LAN by a distributed architecture which provides multiple paths or routes between each pair of communicating entities. This allows information to be routed around or away from faulty network elements (e. g., broken links or down nodes). The network nodes, which provide an interface to the network for the attached systems, could be intelligent devices that execute distributed fault-diagnosis algorithms. These intelligent nodes would monitor the operation of their neighboring nodes to detect erroneous behavior (e. g., babbling devices or devices which place erroneous information on the network) as well as hard systems failures. Faulty systems (nodes or attached processors) would be isolated from the network and replacements could be switched onto the net if the failed unit is of a critical nature. After taking the appropriate corrective action, the DMS would file a failure report to a designated collection center attached to the system. These reports describe what measures are to be taken to bring the DMS back to full capacity. An integrated data network would support the core system and user/ experimenter requirements of the Space Station in a unified network approach. One network might support all of the diverse communication requirements onboard the Space Station, thereby eliminating the need for several heterogeneous LAN's in the DMS. There is considerable interest in integrating voice, data, and video into one system in the U.S. (Dorros, 1983) for such applications as teleconferencing and in Japan for their future Information Network System (Kaplan, 1984).

A primary driver for an integrated services data network design is the performance required to handle video communications. A full motion video capability is required in the Space Station for rendezvous and proximity operations and autonomous systems. Therefore, the DMS should include fiber optics (FO) technology and high-performance nodes which can more effectively utilize the bandwidth inherent in fiber optics (15 GHz/km for single mode FO fibers). In addition, the incorporation of wave division multiplexing (WDM) into the fiber optic network design would allow various types of data (e.g., voice and video) to be transmitted simultaneously in full duplex over a single optical fiber (Hendricks, 1983). The limitations to the WDM technology, as well as to the performance of fiber optics in general, are the electro-optical and optical device technologies (transmitters, receivers, and multiplexers and demultiplexers). Presently, a 4-wavelength point-to-point WDM system is now commercially available (140 MBPS/channel) and an 8-wavelength WDM star bus has been demonstrated in the laboratory.

High performance in a LAN is realized not only by the use of high-speed devices and components but also by the selection of an appropriate architecture or topology. A topology that provides several alternate paths between each source/destination node pair (e.g., a partially connected mesh) can support multiple, simultaneous communications on the network as well as provide fault-tolerant operation. Conventional LAN topologies such as a broadcast bus or a token-passing ring do not possess such capabilities. In addition, alternate path topologies allow traffic to be spread out over the network (traffic balancing) to alleviate congested areas and reduce data delays. This is accomplished through the use of an adaptive routing algorithm embedded in each network node.

The design of efficient protocols for the DMS LAN is seen as a critical system requirement. Protocols which allow dissimilar systems to converse on a network should provide effective error and flow control at all levels. The ISO-7 layer model provides a useful guide for protocol design but attempts to standardize protocol layers which are directed toward less demanding and diverse applications than what are envisioned for the Space Station. Therefore, it is likely that the

protocol design for the DMS will be tailored to meet the Station requirements, perhaps borrowing attractive features from existing standards. Once established, the network protocols will define standards for software interfaces at the higher levels and connectors and components at the lowest level. The lower protocol levels should be the responsibility of the intelligent network nodes. For example, they would be responsible for the delivery of error-free data from source to destination over the net. This would free the attached host systems to perform applications-oriented tasks.

Automation and robotics technologies which have been identified as having impact upon the data management subsystem include intelligent network nodes (electro-optic); robust fault-diagnosis algorithms; and high-performance network components, systems, and architectures. Technology developments required for the data management function include electro-optical devices (transmitters and receivers); optical devices (integrated optical switches, multiplexers and demultiplexers); integrated optical/electrical devices in monolithic GaAs circuits; high-density optical storage device with read/write capabilities; expert systems for configuration and control; and simplified distributed network algorithms. IOC to FOC "scars" relate to ensuring that the initial design of the DMS LAN includes the capability for expansion of capacity and performance to meet anticipated growth requirements.

The operations cost limitations and operations goals of Space Station are planned to reduce the many support personnel typically required to monitor, analyze, reconfigure, and checkout spacecraft digital systems in order to work around in-flight problems. Thus, there will be a need to automate the above tasks in order to attain the required Space Station autonomy.

Fault-tolerant design principles, using automated decision making, can be extended and improved with artificial intelligence techniques and applied at the levels of application software, operating system software, and hardware. At the application level there are often consistency relationships that are useful for identifying and, to some degree, isolating faults. At the level of operating system software, there should be fault-tolerant principles which can be used for fault diagnosis/isolation, state recovery, redundancy management, and function reconfiguration. At the hardware level, Built-In Self Tests and voting mechanisms should be used for handling faults. Audit trails for fault recovery actions need be provided at the system level for maintenance planning and scheduling and at the system/subsystem level for reconfiguration planning.

Typically, fault management is layered, and faults are masked to higher levels. Alternately, higher-level principles, such as analytical redundancy, can be applied to detect and isolate lower-level faults. Generally, higher-level reasoning is neither anticipated by nor passed downward to lower levels. A function of fault management would be to unify fault-tolerant information provided at various system levels (potentially an expert system with heuristic fault analysis of transient faults, trends, and critical combinations of design faults). Extensions of current fault management methods would make use of global information data to identify and isolate both hardware and software faults. It might also provide reliability analysis and maintenance planning, given the current context of fault data, system configuration, reliability, and mission requirements. The underlying layers of fault management itself would be highly adaptable, reliable, and subject to extensive validation.

The advanced automation and robotics technologies which are identified to be involved here include command/display in natural language interfaces, heuristic fault analysis, planning and scheduling, and self-improving tests and diagnostics. Technology developments which are required include representation of procedural knowledge, validation methods for autonomous reconfiguration, fault-tolerant software, reliability and performance analysis, and redundancy management. IOC to FOC "scarring" includes a provision for built-in test equipment. Software "hooks" include provisions for understanding and responding to fault management queries. In order to provide

fault management with an adequate global view for diagnosis and planning, all systems with fault attributes (presumably all) would interact with fault management.

One of the most labor-intensive processes involved with NASA's projects to date has been the design, development, implementation, and checkout/verification of computer software. Automatic programming is a potential means to shortcut some of the long lead time and costs involved in the software development cycle. Automatic programming would allow projects to proceed from a specification of software requirements directly to an operational, thoroughly checked software package capable of performing its designated functions. Automatic programming is predicated on very basic but powerful concepts: having articulate knowledge of software organization (including structure, activities, policies, procedures, and responsibilities) and codification of knowledge in machine-usable form. Knowledge-based software program synthesis with iterative review, revision, enhancement, and validation at the program specification level is the paradigm of automatic programming. An automatic programming capability would be required to meet several basic postulates:

* Smart compiler
* Knowledge-based programming environment
* Self-description and, therefore, self-modification
* A knowledge base containing all knowledge on programming, the system, and project management
* One language (very-high level, wide-spectrum) for stating programs and knowledge

The Kestrel Institute of Palo Alto, California, estimates that an automatic programming facility could improve the software production cycle by a factor of 10 (Rockmore, 1984).

Propulsion

The resupply and maintenance of the RCS systems represent potential applications of advanced automation and robotics technologies. Resupply will require transfer of propellant or propellant tank modules between the logistics module, the Space Station, and the OMV and OTV. Means might be provided to perform or assist this activity remotely. The development of teleoperators, the employment of dedicated small RPV tugs, or the adaptation of the RMS mated to special-purpose coupling mechanisms should be considered to eliminate the need for EVA to connect/disconnect refueling supply lines. Connection lines could be fitted with sensors (including CCD TV's) and actuators to make them "smart" in the sense of being able to perform and verify the connect/disconnect functions, to detect leaks, and to perform at least some emergency safing procedures. In addition, on-station supply of propellent could be done at the thruster level instead of via plumbing. The RMS, a teleoperator, or (eventually) a robotic mobile resupply tanker could carry fuel around the Station for resupply of the individual thrusters. Such systems may also be useful for performing maintenance or for the removal/replacement of thrusters.

Some of the advanced automation technologies identified as impacting the propulsion subsystem are

* Teleoperator and robotics
* Special-purpose sensors/actuators
* Vision systems
* Mobile robots

New technologies required in support of the propulsion subsystem on the Space Station include special connect/disconnect couplers with integrated sensors and actuators, propellant gauging sensors, and advanced monitoring and control technology.

Hardware "scars" which might be effected on the IOC Station include the following:

* RCS systems having provisions for simple replacement capabilities

* RCS modules designed for ease of grappling by teleoperators or (future) mobile robots

One software "hook" which has been identified for the IOC Station is for propulsion fluids management, especially for Station center-of-gravity control. Such a controlling mechanism must also consider other Station fluids. Critical interrelations with other systems and subsystems of the propulsion subsystem include the DMS, which has the responsibility for resupply schedule, fuel inventory, and RCS status information.

Environmental Control and Life Support System

Environmental support for the astronaut crew will require considerable augmentation in capability over previously used space systems. Some elements of the ECLSS can draw on terrestrial experience for already developed technology. Other areas will have to be developed as part of the Space Station program. In particular, the ECLSS could be most effective if automation were incorporated in its control system. Crew time is better spent on higher-level activities than on servicing or tending an essentially static system such as the ECLSS. Nevertheless, crew safety considerations may limit the degree of ECLSS automatic control and autonomous processing allowed at IOC.

The monitoring function within ECLSS is an area in which advanced automation and robotics may be ideally suited for development of new technologies and applications. A considerable group of sensors have been developed which might well be considered for incorporation into a space station module atmosphere monitoring system. A representative example might include diode laser absorption spectrometers (which are capable of detecting minute traces of gases) integrated into an automated gas sampler. Such a gas sampler might be controlled by an expert system whose function it is to analyze the module air quality, detect incipient undesirable trends, and notify the DMS and/or astronauts. Water reclamation is another function which lends itself to a high degree of sensing capability.

ECLSS maintenance might require replacement or refurbishment of subsystem elements which potentially would be flagged by trend detections predicated on sensory inputs. As the ECLSS becomes more extensive (and more complex), expert systems could be utilized to perform the task of interpreting trends or conditions leading to maintenance tasks.

One application that might be considered for the evolutionary Station is an expansion of the expert system element of ECLSS to include an extensive trace gas leak identification capability (particularly for toxic gases). This capability might include suggestions as to where the likely source of the trace component might be, the potential toxicity, and the like. Implied in this is the need for an effective chemical or element composition sensor such as a Fourier Transform Infrared Radiometer (FTIR), laser abosorption spectrometer (LAS), or mass spectrometer.

The advanced automation and robotic technology involved in the ECLSS subsystem includes expert systems and an integrated air/water chemical analysis facility. One major "hook" for the Space Station growth from IOC to FOC is a provision for computer analysis and control of the subsystem which is more knowledge-based than is the initial design and for an integrated fluid management capability.

Thermal Control

The thermal control subsystem on the Space Station can reasonably be expected to be as operationally simple as possible for maximum reliability. Nevertheless, equipping the thermal subsystem with sensors and providing for replacement and repair of external thermal subsystem elements should be considered. Trend monitoring of performance at various points in the chain of

parallel internal and external thermal transport loops can be used to determine maintenance procedures that should be scheduled. Special-purpose end effectors, or eventually robots, could incorporate (1) "sniffers" to locate leaks, (2) thermal sensors, and (3) repair kits equipped to repair leaks. Repair and replacement of thermal radiator elements would most probably be done by means of the MRMS or EVA. Degradation in surface coatings might also be amenable to repair via the MRMS EVA, or crawler robot (teleoperator). Electrospray paint refurbishment should be considered as a candidate technology for application to this as well as other Space Station functions.

The advanced automation and robotics technologies involved in the thermal subsystem include teleoperators with specialized end effectors plus sensors and perceptors. The required technology development for the support of the thermal subsystem is for a space-compatible spray paint adapter for teleoperated end effectors and thermal "sniffers".

Structures and Mechanisms

Mating of the Orbiter with the Space Station is an area that should be considered for automation and robotics techniques. The Orbiter will be required to rendezvous and dock with the Station on a regular basis, but it will also quite likely perform various maneuvers in and around the Station requiring multiple attachment to the Station. Several potential customer/user missions may not be able to accept the shock of hard docking to the Station, nor can the Station continually endure potential disturbances to the GN&C systems, or structural loading that might result. An Orbiter-automated docking or man-controlled docking mechanism should be considered for accommodating these constraints.

It it most likely that man will initially perform much of the assembly of the Station as well as (early) operations involving docking. However, as automation and robotics technologies mature and sensors and perceptors are developed to support more autonomous Station operations, it is anticipated that much of the docking and structure repair and refurbishment can be performed via teleoperations or autonomously by robots.

The identified automation and robotics technologies involved with the Space Station structures and mechanisms subsystem include:

* Sensing and perception (embedded CCD TV cameras, latching detectors, alignment sensors, etc.)
* Advanced workstations
* Actuators
* Teleoperators
* Computer vision

One major technology development which is required for structures and mechanisms is a flexible docking adapter. The Orbiter would have to be fitted with a set of mating points in the bay near the access area to support evolutionary growth of the Space Station in the post-IOC era.

Operational control of an individual space vehicle is a viable candidate for being highly automated on the IOC Space Station. Operations involving station-keeping (i. e., flying in loose formation in the near vicinity of another vehicle) have already been demonstrated to a high degree of reliability in operations involving small satellites. Previous operational space experience has proven the techniques necessary for automatic rendezvous and docking of two vehicles in space. An automatic rendezvous might be employed to bring a vehicle in close proximity so that the Space Station RMS could be used to ease the two vehicles together in the proper orientation to prevent bumping damage.

The portion of the structures and mechanisms section that deals primarily with automation would be the structural deployment verification and the use of the MRMS for the assembly of Space Station structures. Space Station construction represents an excellent opportunity for a robot/teleoperator to prove its worth in

reducing the amount of extravehicular activity required to accomplish this task. Once it has been adopted that a truss system will be employed in the construction of the Station and a way has been determined for a manipulative device to move about upon that structure, then the exact method of construction can be ascertained. In the design of the Space Station, the attempt should be made to make things easy for interfacing to robots or robotic devices. Application of robotics to the Space Station may require that robot mobility be a central design consideration of both the utility/support structure and of all replaceable modules. Advanced automation (AI and robotics) can serve many diverse purposes and is acceptable across most aspects of the operation of the Space Station. There is, therefore, a logical argument for treating AI and robotics as a utility and making them a part of the utility/support structure. This should be avoided because of the rapid rate of change in this field.

Habitability

The Space Station must provide an internal environment adequate to support and maintain crew comfort, convenience, health, and well-being throughout all operational phases. The day-to-day operation of the inhabited environment of the Space Station should be highly automated with only occasional human monitoring required from IOC through FOC. Automation of the control of the environment in the Station will surely undergo further automation with the advent of artificial intelligence and expert system ideas being employed in the monitoring process.

In-flight health care is an absolute requirement for Space Station planning. On-orbit medical care will promote crew safety and maximize performance. An in-flight Health Maintenance Facility (HMF) could also prevent the unfortunate scenario of an unscheduled rescue mission for medical reasons. Health care will embody the triad of prevention, diagnosis, and treatment. Each will use biomedical equipment designed for the Station, along with medical procedures proven in microgravity and medical knowledge derived from terrestrial medicine. The facility must be modular to allow for quick changes in mission emphasis and also to allow for technology advances which permit more utilitarian equipment for diagnosis and treatment. Low-weight, yet low-volume, fully automated diagnostic laboratory equipment must be included in the HMF. Routine clinical chemistry, hematology, microbiology, urine analysis, and toxicological monitoring are essential. A capability must exist to deal with acute critical care and trauma situations. Real-time analysis of physiological parameters for assessing the health of the traumatized patient is a must. Computer-aided statusing of the patient is necessary. On the Space Station, the following health-care functions (and probably many others) should be automated:

* Medical history taking
* Instrumentation-derived data analysis (including real-time monitoring and analysis)
* Medical imaging
* Medical image storage and retrieval
* Medical decision making

The tremendous amount of information required for decision making in medicine and the importance of these decisions have led to investigations of computer-assisted medical decision making. The goals of artificial intelligence in this field are to obtain human-like behavior from a computer program, using symbols to represent the concepts and objects of the medical environment. Expert systems are designed to capture the specialized knowledge of practitioners whose performance is significantly above the norm. Unfortunately, the knowledge used by experts in their problem-solving tasks is not well formulated or well documented, specifically with regards to the medical experts. However, the computer can be used to a great advantage as a medical decision making aid.

Specifically, the incorporation of fault tolerance and fault isolation will significantly contribute to autonomy of operation. However, there is another aspect to

habitability considerations for the Space Station beyond creature comforts, and that is the interface of the crew to the Station and its subsystems. Crew interface is important for several reasons. Knowledge is required by the crew to interface with the multitude of Station subsystems; it is highly desirable that this knowledge be made as transportable as possible from subsystem to subsystem in order to minimize the cross-training required to operate the various subsystems. A standard command structure or the like for all subsystems is probably not feasible because of the diversity of the applications of subsystems. Potentially, however, there is a way for the communication of crew instructions to subsystems to be universal in nature, and that is via voice commands and intructions. Such a system would necessitate an interpreter for speech to be a part of the crew interface of each subsystem. The technology requirements of such a speech interpreter are probably beyond today's state of the art. However, some of the ideas for a speech subsystem will be examined to explore the potential for enhancing Station habitability through automation.

Automation of hematological blood counts by specialized computer vision systems has been available as a part of commercial instrumentation in clinical laboratories since 1977 and should be considered for application to the clinical laboratory hematology section of the Health Maintenance Facility (NASA, 1984d, p. 90). Special machines which are based on cellular logic have proven to be a rapid means of automating white blood cell counts and may require additional development to perform other types of hematological analysis for quick-response medical diagnosis. Applications may exist for microbiological and chemical analysis as well. Rapid, automated medical diagnosis may be a critical issue in dealing with medical problems which require immediate diagnosis before the return of a Space Station crew member to Earth is either possible or medically advisable.

Computer vision and cellular logic machines and operations are the automation and robotic technologies involved in the habitability subsystem. Additional development may be required to extend current technology to broader hematological, microbiological, and chemical analysis applications. The one identified "scar" is for computational vision hardware in the Health Maintenance Facility. Further near-term development of cellular logic applications to medical clinical laboratory processes is an applicable IOC-to-FOC software "hook." Critical interrelations with other systems include the medical expert systems and the information and data systems.

Extravehicular Activity

Whereas the very essense of EVA and its man-intensive nature give pause to consideration of the applications of automation and robotic technologies, certain functions might be amenable to machine assistance. Examples that might be considered are automation in EVA suit cleaning and MMU resupply and maintenance, so that the procedures presently done on the ground can be done on-orbit without overloading crew time. Simplified subsystems for suits which are designed for easy replacement, refurbishment, and repair might be considered.

Many aspects of inspection, monitoring, and proximity operations should be investigated by Phase-B contractors because man-machine partners possess capabilities superior to those of man alone for performing complex tasks which are beyond the reach of complete automation in the foreseeable future. In particular, the man-machine partnership inside the Space Station and in EVA should be scrutinized carefully. A man-machine partnership would combine the analytical and intellectual powers of the man with the quantitative skills of machine sensors and computers. An interesting case study would be man-computer vision. Astronauts will be supplied with EVA TV cameras, so video will be available to a computer which could be added to the astronaut's suit. The principal issue would be miniaturization of necessary computation hardware and man/machine interfaces. Functions to be performed by the computer would be to supply quantitative information on an object's size, orientation, and condition after an astronaut

had identified the object or feature for the computer. As an example, the astronaut, inspecting for erosion in module walls, could point the camera to a suspected problem and ask the computer to supply engineering data on that module part; the computer would then calculate the area of erosion on the surface and supply information on the severity of the problem using engineering data baselines.

Advanced automation and robotic technologies which would be involved with EVA include a computer vision system. Identified technology needs required to support EVA automation include miniturized displays and crew interfaces. IOC "scars" may include a portable computer with appropriate astronaut interfaces. Software "hooks" in the IOC configuration include the specialized software for computer vision applications. One identified critical relationship of the EVA subsystem with other the Space Station subsystems includes a communication link with Space Station primary data base and an air-to-ground link for potential problem resolution.

Other areas which may be considered for advanced automation are the EVA support functions. The servicing of suits and mobility units could possibly be done more effectively by advanced automation and robotic techniques. Also, at least one air lock will be equipped as a possible hyperbaric chamber for emergency use. Automated control of this facility should be considered, as it will be essential for safety.

Verification

System checkout and verification have always been one of the most costly, time-consuming elements in any space flight program. Automation and robotic technologies offer the means potentially to alleviate some of the time and expense required to effectively check out and verify Space Station systems. The A&R applications range from the employment of an integrated test scheduling methodology to the use of knowledge-based expert systems to direct testing sequences themselves. It is obvious that an automated checkout and verification processor would do a better job of performing the highly repetitious functions involved in verification than a human ever could. The availability of an on-line computer-aided-design/computer-aided-engineering (CAD/CAE) data base on the Space Station - which would contain the details of the designs of systems and subsystems - could be utilized potentially by an expert system for the analysis of test anomalies as well as for determining test criteria to be used in the verification process. A great deal of technology development must precede the realization of such scenarios, but the payback potential of such capabilities is tremendous.

It should be pointed out that the application of A&R technology at the subsystem component level is very important in the verification process. The idea of built-in self-test can conceivably be extended from mere simple-minded hardware checkout exercises to intelligent director/monitor capabilities which have the ability to formulate test procedures and sequences as well as effect work-arounds in the event of anomalies. If a subsystem self-healing capability is to be employed on the Space Station, a self-diagnosis capability must be in place to initiate the process. Of course, self-healing implies automatic self-reverification, so the existence of a methodology to effect revalidation of self-healed systems at the component level must be the subject of A&R research. When the capability of self-diagnosis, repair, and verification are in place on the Space Station, it is logical to include with these functions a configuration management feature which would perform automatically and would post the actual system layout to an onboard CAD/CAE data base as appropriate.

While the notions of employing advanced technology for system checkout and verification are clearly beyond the state of the art today, planning for the eventual use of these ideas is essential. Therefore, for the Space Station IOC, system designs should incorporate "scars" such as (1) a variety of sensors which will allow for assessing the health and status of subsystem components, (2) data interfaces so subsystems can communicate with distributed processors, and (3) robust fault-diagnosis (self-test) equipment upon which evolving capability can expand.

While system checkout and verification of space flight vehicles are costly, time-consuming processes, their importance cannot be overstated. A program for automating the processes should be pursued from the standpoints of saving time and money as well as potentially increasing test applicability and accuracy.

CONSIDERATIONS FOR PLATFORMS

As noted in the Reference Configuration (NASA, 1984d), the platform concept has matured and evolved through several stages. In the earliest stages the concept of the unmanned Platform was based on a large structure whose components were copies of components to be used in the manned element. Two platforms were envisioned: one platform in polar orbit and one co-orbiting with the manned Space Station manned element. At the time that the reference configuration was finally completed, the Platform concept had become a relatively small design, and with the polar and co-orbit platforms very similar in basic configuration. To the greatest degree possible, the platforms are expected to use as many manned core elements as possible to help reduce cost. The platforms are assumed to be designed to be serviced on a 2-year cycle with a 1-year contingency. Thus, the platforms are similar to free-flying spacecraft in that they must be very much automatic in their operation, although because they carry experiments controlled from the ground, the automated features do not create an autonomous spacecraft.

NASA has emphasized design for on-orbit repairability in spacecraft for some time, anticipating the utilization of capabilities made possible by the Shuttle's becoming operational. Recent experience in the retrieval and repair of the Solar Maximum Explorer (SME) has demonstrated the effectiveness of this design approach.

Consequently, automation and robotics on the platforms will benefit from techniques already developed, applied, and planned within NASA. The Platforms will have aspects of free-flying, repairable, serviceable spacecraft on the one hand and aspects of the evolvable Space Station core on the other. Moreover, the Platforms are anticipated to carry many instruments which, themselves, have repairability and resupply capability built in. Much automation on the platforms will, thus, be the responsibility of the payload designer and will not have a direct impact on Space Station automation and robotics. Instrument control, data handling, data preprocessing, data preparation, command decoding, fine pointing, ground interaction, and so forth will be handled within each experiment (with certain restrictions). Certain interactions will be constrained, such as instrument failure management, to meet typical spacecraft bus requirements.

Servicing will benefit greatly from robotic applications for the platforms. Plans call for STS and OMV servicing of the Polar Platform while the co-orbiting Platform may be serviced from the STS or OMV, or by rendezvous with the Space Station itself. Since the major part of servicing for the Platforms is instrument modules for instruments themselves and orbital replaceable units for engineering servicing, the utilization of advanced sensory capabilities in the remote manipulator system and on the OMV may be considered to improve work efficiency. Improved work efficiency would be most beneficial in the case of on-site servicing by the STS with its limited on-orbit time.

For the co-orbiting platform more options exist, since this platform can be brought into the proximity operational zone or docked to the Station. In the latter case the capabilities developed for the Station (and addressed earlier in this section) could be utilized to perform servicing.

One additional aspect of servicing in the remote modes (via OMV) is the need to provide communication and particularly the vision aspect of teleoperation or telepresence.

Communication to and from the Space Station could, during proper orbital planning, be via radio-frequency or laser communication link to avoid TDRS/TDAS link time delays. In addition, heads-up displays could be considered with integrated information display to

facilitate the teleoperation function. If practical means can be incorporated to give three-dimensional display and computer-generated perspective views from stored platform image data, the astronaut performance might be enhanced in the servicing operation.

Communication itself has other aspects which might benefit from automation. Expectations of data rates and volume from the Platform instruments are in the range of 10^8 bits per second and total data 10^{11} bits per operational event, respectively. Certainly, saturation of TDRS/TDAS is a possibility when the entire Space Station Constellation data rate and volume are taken into account. A dynamic scheduler and communications controller for the Space Station Constellation (Manned Core and two Platforms) might be required to properly allocate communications channels and times to avoid conflict. Humans are not capable of handling this task, since orbit phasing shifts constantly and since communication must be dynamically managed over orbit-to-orbit time intervals.

CONSIDERATIONS FOR SPACE STATION OPERATIONS

The applications of automation and robotics technologies to Space Station operations are presented in two parts. The first topic to be addressed is the application of A&R technologies to functions which should result in decreased operations requirements. Next to be presented is a discussion of the applications of A&R technologies to operations and procedures to mechanize some of those functions.

The identification of appropriate roles for man and machine is extremely important from the standpoint of developing a sound, cost-effective IOC and growth station design. It can be very costly to pursue an arbitrary technology development plan without having first defined the proper functions to automate related design cost impacts and R&D risk.

For purposes of assessing crew productivity impacts, two factors must be evaluated: (1) detailed component failure frequencies and (2) time required to resolve each type of failure. The product of these two variables yields "hours/mission cycle." If this product can be estimated for various classes or groups of components (e.g., batteries, fuel cells, solar arrays, etc.), assessment of man/machine alternatives for a given subsystem can be placed on a more rational basis.

Skylab docking experience indicates that roughly 8 to 10 hours was required for the complete docking process. However, the Shuttle Operations group has suggested using 4 to 7 hours because of improvements in technology and crew training. The key productivity aspect of the docking process is the fact that during docking maneuvers at least two individuals are generally monitoring and performing command and control functions for the full 4 to 7 hours. Although not a productivity problem under present Shuttle operations, the planned biweekly Shuttle and orbital maneuvering/orbital transport rendezvous and docking could consume a sizable amount of time using present procedures (Langley, 1984). Structural manufacturing (stress situations) and system assembly will have the greatest impact on station crew productivity and safety during the period around IOC, when assembly activities are highest. During this period, considerable EVA and ground support will be required. In conjunction with the assembly function, a sizable amount of mission planning will also be required by the ground crew, with a gradual shift to the station crew in later years.

The Space Station RFP (NASA, 1984e) system level requirements delineate crew productivity (as related to mission completion) and safety as key design considerations.

Table 2, based on Skylab and Shuttle experience, clearly shows that the individual productive time available is on the order of 10 hours per mission day. This productive time must include subsystem operation, monitoring, calibration and fault diagnosis/correction, operations planning, EVA, rendezvous/docking, and miscellaneous housekeeping as well as experimentation, observation, manufacturing, and other user-related work. Clearly, it will

be advantageous, if not essential, to automate many of these tasks.

TABLE 2.- APPROXIMATE ON-ORBIT TIME AVAILABLE FOR COMMAND/CONTROL TYPE FUNCTIONS (HR/PERSON/DAY)

Housekeeping Functions	Hr/Person/Day
Presleep Activities	0.7
Sleep	8.0
Postsleep Activities	.7
Meal Preparation	.3
Meals	1.0
Postmeal Cleanup/Biocide Application	.3
Waste Water Dump	.3
Supply Water Dump	.3
CO_2 Absorber Replacement	.3
Fuel Cell Purge	.2
Check Safety Devices	.6
Crew Free Time	1.0
Subtotal	13.7
Productive Time Available	24 - 13.7 = 10.3

As an example, consider the monitoring and verification activities associated with command and control tasks. Presently, the monitoring function is done primarily via ground control. Loftus (1983) reports that roughly 70 percent of the monitoring points are automatically telemetered to ground control. The remaining 30 percent, or approximately 1000 data elements, are monitored by the crew onboard. Using a standard scan rate of 1 second per data element (as confirmed by Shuttle experience) and monitoring twice a day per standard procedures, a total time of 0.6 hour per day results (Freeman, 1980). If the monitoring function were to be completely autonomous from the ground, existing procedures would require an additional hour per day to complete the monitoring function.

The verification and calibration function is generally more complicated because it usually requires more than one instrument reading, a comparison of data from either ground control or other instruments onboard, and, possibly, a spacecraft control decision followed by a system command and followup verification. Both Skylab and Shuttle operational histories suggest that verification and calibration functions require on the order of 0.3 crew hours per function per day. Table 3 provides an extrapolated baseline list and estimated times of Space Station verification and calibration tasks based on present verification or calibration experience and the previous conceptual design.

TABLE 3.- POTENTIAL SPACE STATION VERIFICATION/CALIBRATION FUNCTIONS

Functions/Tasks	Approx. Time (Hr/Day)
Plan Mission	0.5
Verify/Calibrate	
• Inertial Unit	.3 (Done Twice/Day)
• Docking system	.3
• Accelerometers at Structural Extremities and GNC, e.g., Global Positioning System (GPS)	.3
• Thermal Control Systems	.3
• Structural and Mechanical Loads	.3
• Station, Experiment and Platform Pointing or Relative Alignment	.3
• Power Subsystems	.1
• ECLS Subsystems	.1
• Experiment Instrumentation	.6
• Test Instrumentation Onboard	No Value
Parameter Updates and Data Storage in Preparation for Next Verification/Calibration Exercise	.1
Total Approximate Daily Time:	3.8 (4)

Verification and calibration functions may require that a command and control decision be made, followed by a change in state of a given subsystem or the station as a whole (e.g., change in station attitude to allow for platform accommodation). The command and control function initiated by the station or ground crew is generally a semiautomated function requiring minimal crew interface (i.e., initiation of control sequences by switch activation). Therefore, it appears that the major tax on the crew lies with (1) the monitoring and verification functions which provide the inputs used in making command and control decisions and (2) making the proper decisions and initiating the appropriate followup control sequence.

System anomalies and failures require both troubleshooting and decisions concerning corrective actions. Both Skylab and Shuttle operational logs indicate that the resolution interval can vary from 5 minutes to hours, and in some cases days; one example is the problem with the Skylab Control Moment Gyro (CMG). In some cases a failure is never resolved. The erratic behavior of the Skylab CMG's is an excellent example of an unresolved failure which had a major impact on crew productive time and safety. Overall, Skylab experienced a system anomaly or failure on the average of once every two mission days.

The Space Shuttle failure history analysis has not been completed to date. Therefore, only summary information is provided here. Overall, the more recent missions have seen a major reduction in failures from an average of six anomalies or failures per mission day to four. The Shuttle Quality Assurance Office reported that over the 13-flight span, literally all avionics and instruments have failed at one time or another; major structural and mechanical failures have included thermal protection, brakes, and landing gear; software problems have generally involved initiation format errors caused by not reformatting all other linked programs when a reprogramming change was incorporated; electromechanical failures have involved TV cameras, recorders, printers, actuators and door mechanisms; fluid problems have included leaks in coolant system along with valve, pump, and fuel cell failures; finally, electrical problems have typically been with heaters, thermostats, wiring, circuit breakers, and switches.

Besides troubleshooting and repair activities associated with the station itself, the onboard and external experiments or manufacturing will also require periodic servicing. Skylab experienced a small number of "unscheduled" experiment problems. As a start toward understanding the minimum servicing requirements for experiment or manufacturing processes, consideration should be given to periodic planned maintenance for several of the experiments. The major concern here is the potential frequency at which EVA may have to be employed to service the external station experiments and the platforms.

The combination of the anomaly/failure frequency and the drain on crew productive time asserts troubleshooting and maintenance as critical functions.

Accepted human engineering standards suggest that the following key criteria be used for determining when to automate functions (Van Cott and Kinkade, 1972; Von Tiesenhausen, 1982):

(1) Automate to avoid perceptual saturation.

(2) Automate to reduce concurrent tasks.

(3) Automate tasks on compressed timelines.

(4) Automate to avoid human bandwidth limitations.

(5) Automate routine tasks.

(6) Automate memorization tasks.

(7) Automate sequential and time tasks.

(8) Automate monitoring tasks.

(9) Automate time consuming, boring, or unmotivating tasks.

(10) Automate emergency-prevention devices.

(11) Automate complex mathematical or logical tasks.

(12) Automate complex tasks that must be performed rapidly.

(13) Automate to enhance system reliability.

(14) Automate safety endangering tasks.

(15) Automate systems with consideration to crew acceptance.

The crew acceptance element is extremely important, as will become apparent in the following discussion.

The network analysis indicated subsystem checkout and fault repair as major man/machine interfaces. Consideration will be given to the fault repair function first. Existing Skylab and Shuttle failure histories indicate that power anomalies and failures occur on the order of one every 17 (Skylab experience) and 2 (Shuttle experience) mission days, respectively. Even though anomalies may not result in actual component failures, they still require frequent monitoring and troubleshooting time intervals, which detract from the valuable 10-hour customer productivity envelope and therefore assert maintenance as a critical function. Skylab and Shuttle operation logs report a fairly wide range of time for correcting anomalies and failures, ranging from 5 minutes to hours. EVA has been suggested for maintenance of power components external to the pressurized modules. Although state-of-the-art, EVA is extremely time consuming (3 to 4 hours is generally required for prepreparation planning activities, donning and checking out the equipment, and depreparation activities). Additionally, EVA does have several hazards associated with it (e.g., variable pressure environments, potential suit punctures, uncontrolled decoupling from the spacecraft, etc.). Out of the above list of criteria, items 3, 9, 11 and 14 directly apply. Item 3 applies because EVA is a time limited activity. Item 11 is germane because troubleshooting anomalies, or faults, can be a very complex process of elimination. Item 9 applies because EVA is time consuming. Item 14 of course applies because of the EVA-associated hazards. The key thrust here is that EVA is not eliminated but reduced in frequency. Therefore, it appears that fault management is a good automation candidate. As a spinoff, if fault management were automated then it appears that the subsystem assembly and checkout functions might be simplified for either on-orbit or ground crews.

Similarly, the mission monitoring, verification, fault management and docking activities controlled from the command and control modules can be evaluated. Table 3 suggested that monitoring, verification, and calibration functions could consume about 4 to 5 hours per mission day, or roughly 40 to 50 percent of the 10 hours available productive time. Information received from the Shuttle operations planning group suggests that, with the exeception of experiments, monitoring, verification, and calibration functions are considered repetitive and time consuming by the crew and are therefore good candidates for automation. Additionally, verification tasks can run in parallel and therefore pose a sizable problem in information sorting and assimilation. By automating both monitoring and verification and calibration tasks, the system would be in direct consonance with items 1, 2, 4, 5, 6, 7, 8, 9, 11, and, in particular, item 15, the crew acceptance element. In the case of experiments, the sheer quantity may make the verification and calibration functions unmanageable without the help of automated monitoring and calibration devices.

However, care must be taken when assessing automation concepts for this area because of

* The potentially large number of nonroutine tasks (which may make the function difficult and costly to automate)

* The potential interface problems associated with having to monitor, collect, and compare a vast array of different experimental variables and data formats

* The constantly changing variety of experiments

The mission planning and maneuvering tasks present interesting outcomes when measured against the automation criteria. Mission planning and maneuver initiation tasks are at opposite ends of the time spectrum. Mission planning requires much more time than activating a switch for a maneuvering command. The planning task requires consideration of many different control variables, tradeoffs, and time windows. In accordance with items 1, 2, 3, 4, 11, and crew acceptance 15, this task is a reasonable candidate for automation. Similarly, although the time required to initiate a maneuver is small, consideration of numerous control

variables and time windows makes planning and maneuvering very similar. Nevertheless, the astronauts voiced concern over arbitrarily giving up manual control. Tasks such as reboost or maneuvering for thermal control are considered too critical for the crew to relinquish. Clearly, this is an area that requires further definition. Along these lines, the results of the docking tasks are equally interesting.

Discussions with the Shuttle Operations Group indicate that the final fine alignment and actual docking functions are two tasks the crew particularly prefers to control. The several hours of rendezvous monitoring fit nicely under items 5, 6, 7, 8, and 9 of the automation criteria.

In summary, it appears that monitoring, verification and calibration, fault isolation and management, station assembly, EVA, mission planning, rendezvous, and limited aspects of station state changes are reasonable automation candidates.

Analysis should be performed at a level of detail sufficient for each of the automation candidates to be associated with the various Space Station subsystems. As an overview, Table 4 relates each candidate automation function with its applicable subsystem in the overall Space Station System hierarchy. This table indicates which functions appear reasonable to automate within each subsystem. For example, automation of potential EVA's (such as module changeout or in-place maintenance) is associated with power, propulsion, thermal control (radiators), structures, and external payloads because these subsystems are largely external to the pressurized areas of the station. Similarly, automation of the mission planning function is associated primarily with communication and tracking, data handling, crew systems, and payloads (i.e., sequencing assembly and initiating experiments). In developing the foundation for a system autonomy and automation plan, it is essential to understand the overall function allocations by subsystem. Table 4 provides this top-level system view.

TABLE 4.- RELATIONSHIP OF AUTOMATION FUNCTIONS TO SUBSYSTEMS

Space Station Subsystems	Automation Candidates						
	Monitoring	Verification Calibration	Fault Isolation/ Management	EVA	Mission Planning	Rendezvous/ Docking	Subsystem State Change
Power	X	X	X	X*	X*		X*
Guidance, Navigation, and Control	X	X	X			X	X
Communication and Tracking	X	X	X		X	X	X
Data Handling	X	X	X		X	X	X
Propulsion	X	X	X	X		X	X
ECLS	X	X	X				X
Thermal	X	X	X	X			X
Structures/ Mechanisms	X	X	X	X*	X*		X
Crew Systems		X	X		X		X
Payloads	X	X	X	X*	X*	X	X

*Mission planning and EVA functions apply to both station assembly and servicing.

The potential for the application of A&R technology to Space Station operations is most promising. Planning and the scheduling of the highly repetitive functions involved with operations are key candidates for automation. The Mission Planning and Analysis Division at JSC has demonstrated a prototype of a knowledge-based system named NAVEX for assuming some of the role of the ground navigation console function for Shuttle missions. The Artificial Intelligence Office at JSC has developed a prototype demonstration expert system for ground operations support of the Shuttle pressure control system to demonstrate applications of automation to most of the operation of a complex system. The adaptation of knowledge-based expert systems for performing flight operations tasks like consumables budgets, electrical power management, and other labor-intensive ground monitoring functions - especially those involving trend analysis - is limited only by the state of the art of today's technology. Research in A&R technologies should bring maturity and utility to these tools and make automated operations a reality.

CONSIDERATIONS FOR CUSTOMER PAYLOADS AND EXPERIMENTS

Customer payloads and experiments are by their nature relatively independent, self-contained flight packages which will probably rely on the Space Station only for such

services as power, thermal control, scheduled data dumps, command interface, and gross pointing. While it is the responsibility of the individual customers involved to incorporate automation and robotic technologies into their flight packages, it is obvious that the more automation utilized, especially for failure recovery, the better the chances for successful project and experiment completion. Based on today's technology, it is difficult to automate research, but ancillary research activities such as data collection and experiment monitoring are functions which are well suited to be automated. Processes which require precision, timeliness, repetition, and/or sequencing must be at least partially automated in order to be effective. The application of advanced A&R technology to these functions to maintain production continuity has been pointed out by General Electric (1984). The application of A&R technology to customer payloads and experiments will also enhance the fall-back position of packages which experience on-orbit repairable failures. Since crew intervention and support will be a very limited resource (especially considering timeliness of repair to meet critical-event windows), the chances of a successful experiment and payload flight could certainly be enhanced by the existence of an automated self-repair feature. A knowledge-based expert system could also be a tremendous boon to payloads and experiments. The incorporation of sensors throughout flight packages would allow an expert system the capability to ascertain status at the component level and to formulate corrective action predicated on sensed trends before hard failures could occur. An expert system could also provide conflict avoidance and resolution for payloads and experiments having time-critical windows and/or targets of opportunity. In short, expert systems are very promising for the enhancement of payload and experiment flight success. Appropriate "scarring" at IOC for growth may require provisions for the necessary sensors to support the eventual applications of expert systems.

The utility of an automated space robot has tremendous implications for maintenance and refurbishment of customer payloads and experiments. One particular "scar" which has been identified for the IOC Station to allow for the eventual use of intelligent robots is to employ a design philosophy of making experiment and payload subsystems serviceable by teleoperated devices. The eventual assumption of service and maintenance tasks by an automated robot will be more easily effected if the tasks are initially designed for teleoperation.

Chapter 5

REPRESENTATIVE EXAMPLES OF AUTOMATION AND ROBOTICS APPLICATIONS

Several representative examples of specific applications of automation and automation techniques for Space Station systems and functions are presented below. While the list is not exhaustive, a number of specific applications are detailed to provide illustrations of potential applications for Space Station systems. It is important to realize that even with a high degree of automation available in some initial system designs, it is most certain that maturing technologies will be available for the growth Space Station. It is expected that the Space Station definition activities will identify additional functions which will be amenable to automation and robotics and that the most promising of these should be considered for incorporation in the A&R plans.

Five studies were performed as a part of the support provided to the Automation and Robotics Panel (ARP). These studies were designed to complement the broader view of the ARP by performing a vertical cut in specific functional areas. By focusing on specific Space Station activities, the objective was to identify major issues and applications. No attempt was made to establish a priority basis for selecting the specific Space Station activity singled out as the study subject. However, the areas selected were chosen to be important and illustrative. The topics for the funded studies were Autonomous Systems and Assembly, by Martin Marietta Corporation; Subsystems and Mission Ground Support, by Hughes Aircraft Company; Space Manufacturing, by General Electric; and Satellite Servicing, by TRW. The fifth study in this group, performed at no cost by the Boeing Aerospace Company, was the operator systems interface, which also includes an in-depth analysis of technology development forecasting for the specific area of operator-systems interface. Some of the results of these studies, as they bear on automation and robotics, are presented below. While in-depth, these studies are by no means exhaustive, nor even necessarily representative of actual elements of the Space Station Program. However, they do provide (1) specific results and recommendations in the areas under consideration, (2) illustrations of possible approaches to performing these types of functions, (3) sources of ideas to stimulate thought in other or similar areas, and (4) identification of specific or generic technologies that need further development.

AUTONOMOUS SYSTEMS AND ASSEMBLY OF LARGE STRUCTURES

Martin Marietta (1984) studied the use of autonomy and autonomous systems to implement Space Station functions, especially the assembly and modification aspects. The following key technology needs for A&R in the Space Station were identified (in the order of priority):

* Teleoperation (remote control)
* Proximity, touch, and force sensing
* Predictive displays
* Low-weight dextrous arm
* Dual arm coordination (figure 6)
* Advanced actuators
* Knowledge-based and expert systems
* Planners, both strategic and tactical
* Range and image understanding
* Special-purpose and multifingered end effectors for robots (figure 6)
* Multisystem coordination (figures 7, 8, and 9)

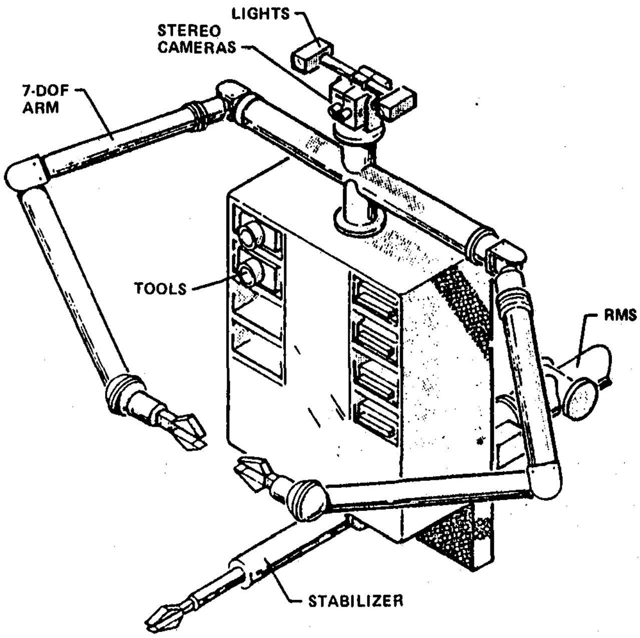


Figure 6.- Concept of telepresence end effector for the RMS (Martin Marietta, 1984).

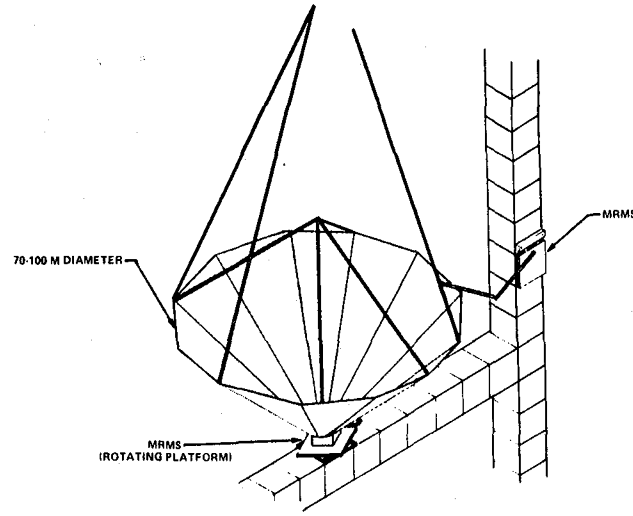


Figure 7.- Multisystem coordination concept for assembly of an advanced commercial communications system, a geostationary platform, at the Space Station (Martin Marietta, 1984).

In addition, the study identified general specific "hooks" and "scars" that need to be considered for an evolutionary Space Station, namely:

* Subsystems with fault-tolerant computers
* Accommodation of network growth potential
* Labeling, marking, or coding of modules
* Providing attachment points (handles and fixtures)
* Providing updatable knowledge bases
* Providing test points
* Modularizing subsystems

COMMUNICATION SUBSYSTEMS AND MISSION GROUND SUPPORT

Hughes Aircraft Company (1984) investigated three technology areas that potentially offer significant automation: (1) digital telephony, (2) automatic speech recognition and synthesis, and (3) data compression. Recommendations applicable to automation and robotics in the Space Station are as follow:

* Process user requests for communication services by an automated real-time system (figure 10)
* Perform automated short-term planning and scheduling of Space Station resources on the Station
* Implement a system for automated payload command screening
* Consider automatic speech recognition and synthesis as a basic mode of man/machine interaction for command and control during the design and development of the Station (figure 11)
* Design the data management system and other subsystems of the Space Station to accommodate fully automated fault diagnosis, isolation, and recovery within the monitoring function of the DMS.

The "scars" recommended to allow for growth and evolution of Space Station

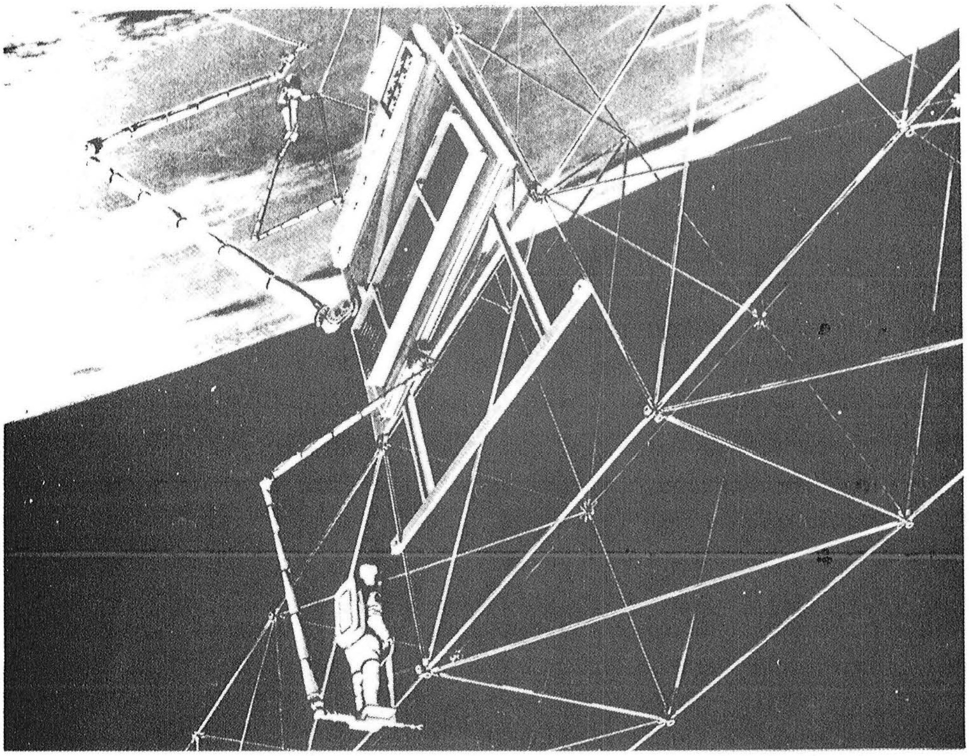


Figure 8.- Second generation MRMS artist concept with astronauts in EVA (Martin Marietta, 1984).

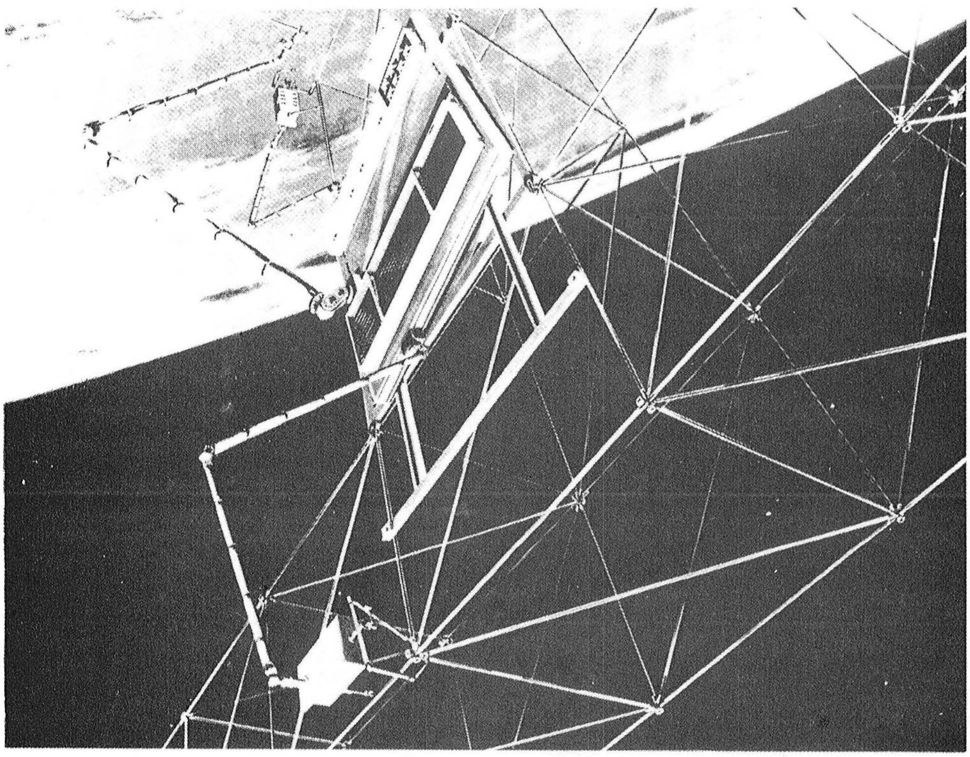


Figure 9.- Third generation MRMS artist concept with special end effectors replacing EVA astronauts (Martin Marietta, 1984).

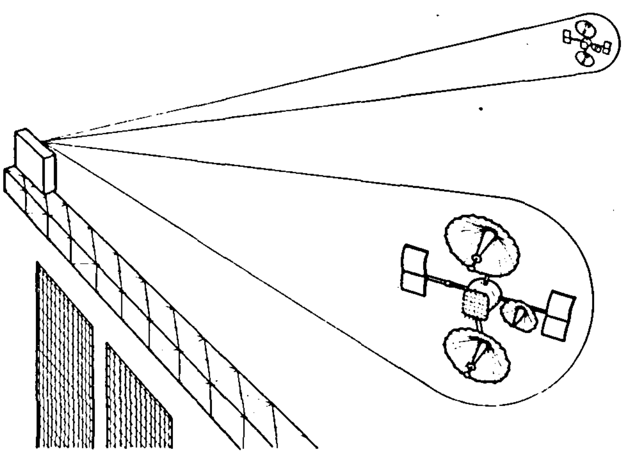


Figure 10.- Concept using multibeam phased array for communications with co-orbiting platform (Hughes Aircraft Company, 1984).

communications control are in the following areas:

* Resource scheduling - allows growth toward real-time expert system

* Command constraint checking - allows growth toward a real-time rule-based expert system

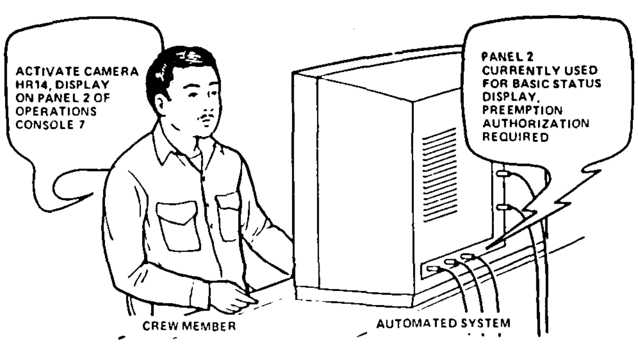


Figure 11.- Illustration of automated speech recognition and synthesis (Hughes Aircraft Company, 1984).

SPACE MANUFACTURING CONCEPTS

General Electric (1984) assessed over one hundred potential Space Station experiment and manufacturing concepts and selected two manufacturing design concepts for in-depth development of automation requirements.

* Gallium arsenide electroepitaxial crystal production and wafer manufacturing facility (figure 12)

* GaAs VLSI microelectronics chip processing facility (figure 13)

The two processes should evolve toward full automation in maintenance, repair, and refurbishment (figure 14). One unique aspect of a space manufacturing facility compared to a terrestrial factory includes the inability to bring technicians and specialists in for maintenance and malfunction repair. Therefore, the advanced automation technology requirements identified by the study are those systems required to remotely monitor and diagnose and to automatically reconfigure, maintain, and repair in the event of malfunction. These requirements embrace a broad spectrum of enabling technologies ranging from ultimate expert systems which monitor, diagnose, and reconfigure to teleoperators and robotic manipulative systems that perform manufacturing, servicing, and repair functions under supervisory control from either the Space Station or the ground.

SATELLITE SERVICING

Among the significant results concerning automation and robotics issues related to satellite servicing (TRW, 1984) has been the estimated 40- to 60-percent savings in crew time for four representative, but diverse, servicing scenarios. These scenarios are outlined in figures 15 through 18. Each figure shows a sketch of the mission concept and lists scenario highlights and key automation requirements. Also shown are estimated hours of crew activity required, with and without automated servicing support.

In addition, TRW identified 12 key automation technologies used in servicing and assessed both the current and projected technology statuses as well as the priorities of these technologies. Table 5 summarizes these results.

Growth was also addressed in the TRW report under the assumption that servicing functions would be required to expand as

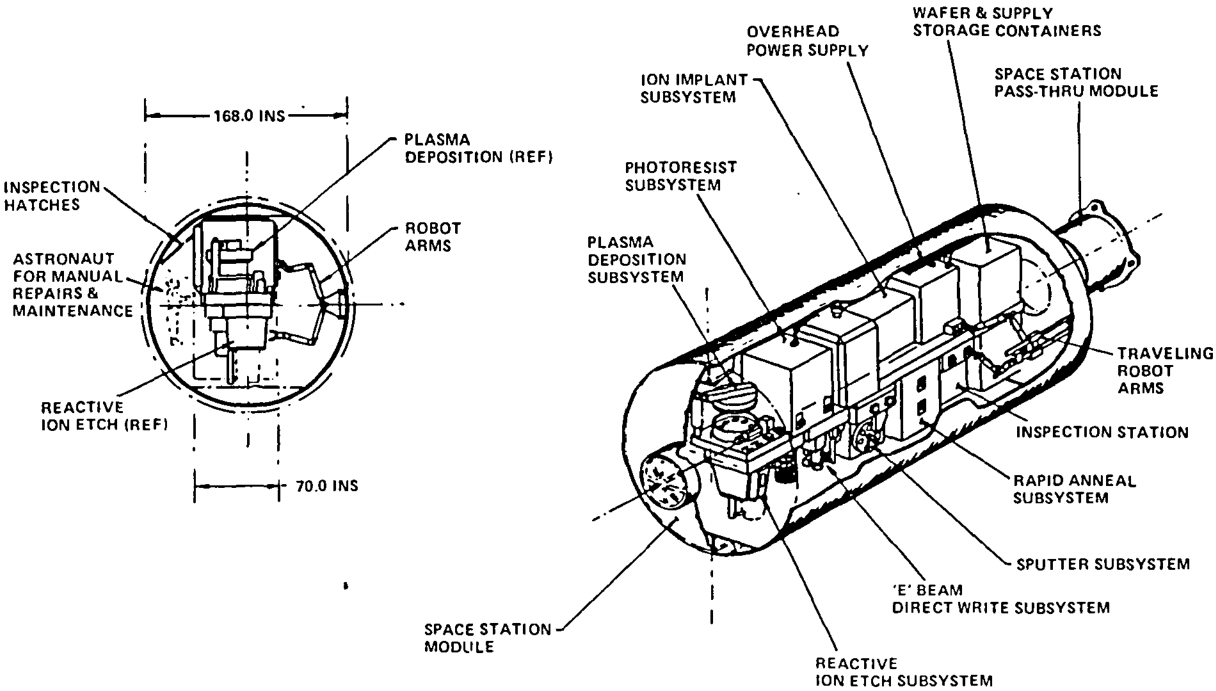


Figure 12.- Automated gallium arsenide microelectronics chip processing facility concept (General Electric, 1984).

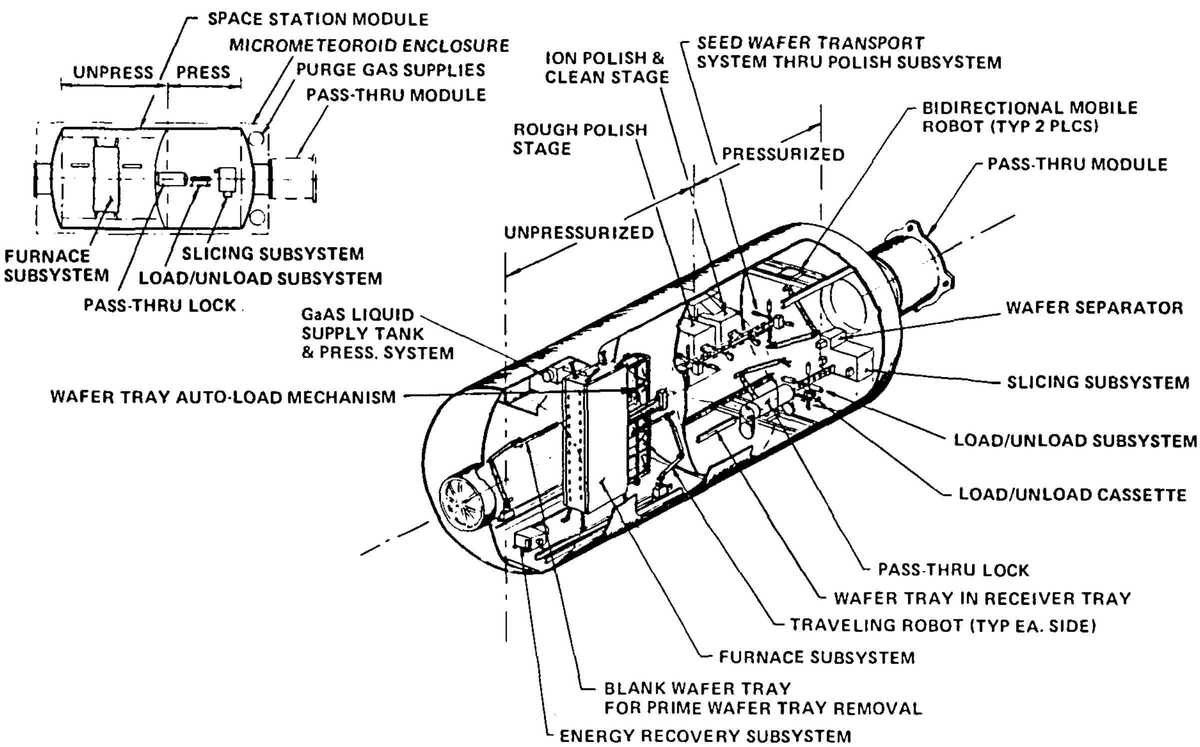


Figure 13.- Crystal production and wafer manufacturing facility concept (General Electric, 1984).

TABLE 5.- AUTOMATED SERVICING TECHNOLOGY ASSESSMENT

KEY TECHNOLOGY	STATE OF TECHNOLOGY			ENABLING TECHNOLOGY	ENHANCING TECHNOLOGY	PRIORITY RANKING
	NEAR-TERM	INTERMEDIATE	LONGER TERM			
1. DEXTROUS MANIPULATORS, INC., SPECIAL END EFFECTORS	X			X		1
2. SERVICING/AUTONOMOUS SERVICING COMPATIBLE SATELLITES AND PAYLOAD UNITS	X			X		1
3. SPACE-QUALIFIED ROBOTS, ROBOTIC SERVICING		X		X		1
4. DATA SYSTEM SERVICING SUPPORT	X				X	1
5. ADVANCED MAN/MACHINE INTERFACES		X			X	1
6. ADVANCED FLUID TRANSFER SYSTEMS		X		X		1
7. ROBOT-VISION CONTROLLED SERVICING		X		X		1
8. AUTOMATED LOAD HANDLING AND TRANSFER			X		X	2
9. AUTOMATED RENDEZVOUS, BERTHING, AND PROXIMITY OPERATIONS		X			X	2
10. OMV WITH SMART FRONT END		X		X		2
11. KNOWLEDGE-BASED SYSTEM SUPPORT (TROUBLE-SHOOTING, PLANNING, CONTINGENCY RESPONSE)			X		X	3
12. REUSABLE OTV			X	X		3

servicing responds to demand. Seven advanced technology provisions have been suggested to facilitate the increasing capability:

* Advancement from teleoperation to robotic operation - an "intelligent" robot

* Refinement of teleoperators and manipulators - greater dexterity, more telesensing, touch sensors, and robot vision

* Increased use of machine intelligence - expert systems for diagnostics, troubleshooting, mission planning, logistics control, and other fields

* Increased data system support to the crew and automated operations

* Automatic traffic control, rendezvous/berthing control to meet greater traffic flow and to ensure safety

* Automated load handling and transfer, commensurate with increased traffic flow of equipment and supplies

To accommodate satellite servicing on the Space Station, TRW proposed a cylindrical hanger concept (figure 19) as a service bay. A dextrous manipulator for teleoperated or robotic application is used within the facility, having access to any part of the satellite being serviced by being attached to the RMS or a movable crew support arm.

Report conclusions from TRW (1984) are summarized in eight major points, as follows:

* Automation can make satellite servicing more productive, but accelerated development of automation hardware is needed.

* Servicing poses automation requirements significantly different from those of other Space Station orbital activities.

* Telepresence is the principal automation discipline required to handle task diversity and unforeseen situations.

* Teleoperation or fully automated (robotic) use of the same manipulators offers flexibility and adaptability.

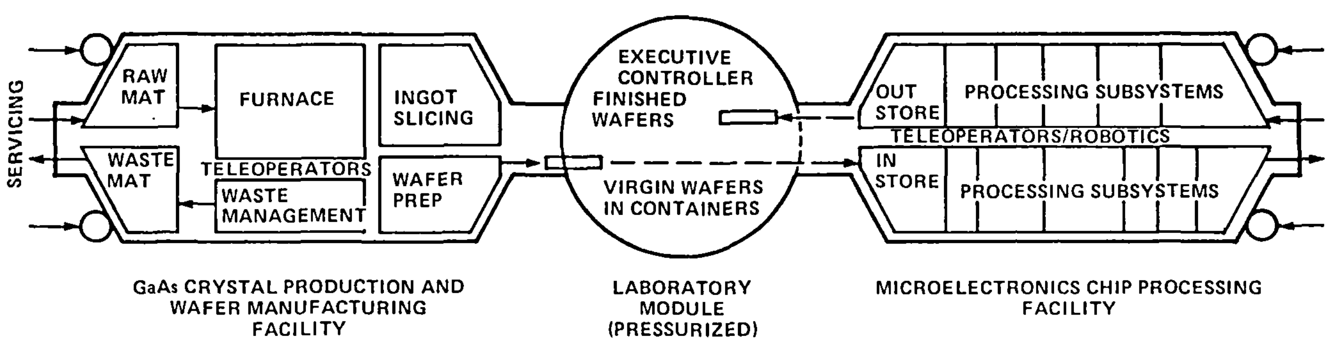
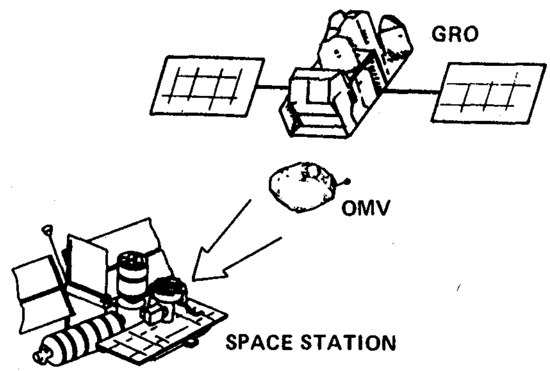


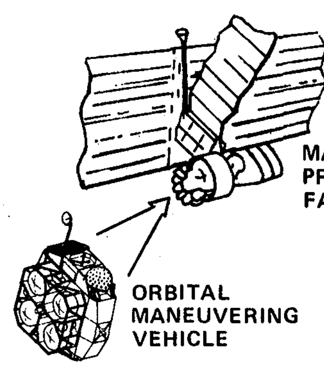
Figure 14.- Overview of the GaAs manufacturing facilities concept (General Electric, 1984).



1. SCENARIO HIGHLIGHTS
   - OMV RETRIEVES GRO FROM 400-KM ORBIT
   - RENDEZVOUS AND BERTHING AT SS
   - COMPREHENSIVE GRO STATUS TESTS
   - REPLACEMENT OF FAILED UNIT(S)
   - PROPELLANT REFILL
   - GRO CHECKOUT AND REDEPLOYMENT
2. AUTOMATION REQUIREMENTS
   - REMOTE CONTROL OF GRO RETRIEVAL
   - AUTOMATED RENDEZVOUS AND DOCKING AT SS
   - LOAD HANDLING AND TRANSFER BY TELEOPERATION
   - PROPELLANT REFILL
   - AUTOMATED TESTS, CHECKOUT, AND COUNTDOWN
   - DATA SYSTEM SUPPORT (DATA DISPLAY, DIAGNOSTICS, TROUBLESHOOTING)
3. CREW ACTIVITY COUNT

   ESTIMATED ELAPSED TIME:
   10.5 HR WITH AUTOMATION
   20.5 HR WITHOUT AUTOMATION

Figure 15.- Reference mission no. 1: Servicing GRO satellite on the Space Station (TRW, 1984).



1. SCENARIO HIGHLIGHTS
   - OMV ATTACHED TO SERVICING MODULE CARRYING FRESH SAMPLE MATERIAL
   - OMV TRANSFERS TO AND PERFORMS RENDEZVOUS AND BERTHING AT MPF
   - SERVICER EXCHANGES SAMPLE MAGAZINES AT MPS UNDER REMOTE CONTROL
   - OMV PERFORMS MPF ORBIT REBOOST
   - RETURNS TO SS; DELIVERS FINISHED SAMPLES
   - OMV REFURBISHED FOR NEXT USE
2. AUTOMATION REQUIREMENTS
   - LOAD HANDLING AND TRANSFER AT SS BY TELEOPERATION
   - RENDEZVOUS, DOCKING, AND BERTHING
   - SAMPLE MAGAZINE CHANGEOUT
   - MPF ORBIT REBOOST BY OMV
   - AUTOMATED CHECKOUT AND COUNTDOWN
3. CREW ACTIVITY COUNT

   ESTIMATED ELAPSED TIME:
   4.8 HR WITH AUTOMATION
   11.8 HR WITHOUT AUTOMATION

Figure 16.- Reference mission no. 2: Servicing free-flying materials processing facility (TRW, 1984).

1. SCENARIO HIGHLIGHTS
   - INSPECT PAYLOAD OR SUBSYSTEM TO BE SERVICED
   - CALL FOR AND RECEIVE REQUIRED PARTS OR SUPPLIES VIA ORBITER
   - TRANSFER SERVICING OBJECT TO AND FROM WORKSTATION
   - PERFORM REPAIR, REFURBISHMENT, AND MODULE REPLACEMENT
   - CHECK OUT AND RESTORE TO NORMAL OPERATION
2. AUTOMATION REQUIREMENTS
   - LOAD HANDLING AND TRANSFER
   - AUTOMATED TESTS, DIAGNOSTICS, AND CHECKOUT
   - MODULE REPLACEMENT BY TELEOPERATION
3. CREW ACTIVITY COUNT

   ESTIMATED ELAPSED TIME:
   2.9 HR WITH AUTOMATION
   6.5 HR WITHOUT AUTOMATION

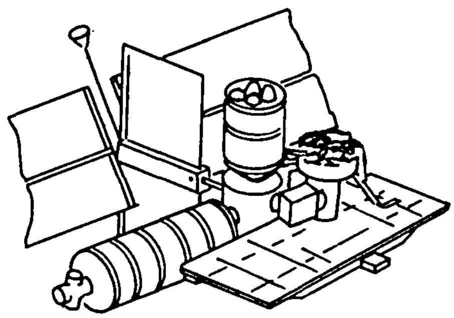
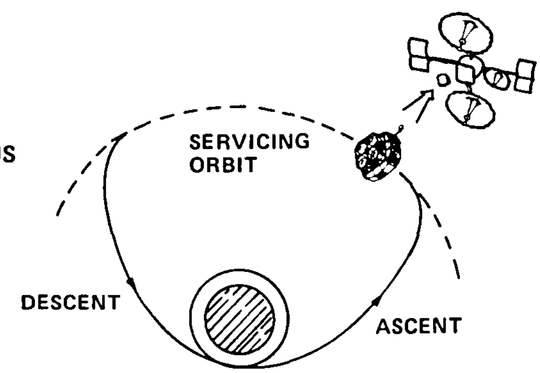


Figure 17.- Reference mission no. 3: Servicing of Station-attached payload or subsystem (TRW, 1984).

1. SCENARIO HIGHLIGHTS
   - CALL FOR AND RECEIVE NEEDED SUPPLIES VIA ORBITER
   - ATTACH SERVICING MODULE TO OTV
   - TRANSFER TO SYNCHRONOUS ORBIT; RENDEZVOUS AND DOCK WITH TARGET SATELLITE
   - CHECK OUT; REPLACE FAILED MODULE AND/OR REFUEL SATELLITE
   - RETURN TO SS (POSSIBLY BY AEROBRAKING MANEUVER
2. AUTOMATION REQUIREMENTS
   - LOAD HANDLING AND THRUSTER ON SS
   - ASSEMBLE SERVICING VEHICLE WITH OTV
   - AUTOMATED CHECKOUT AND COUNTDOWN
   - ORBIT TRANSFER, RENDEZVOUS, DOCKING, AND BERTHING
   - INSPECTION
   - MODULE REPLACEMENT
   - REFUELING



3. CREW ACTIVITY COUNT

   ESTIMATED ELAPSED TIME:
   11.1 TO 13.1 HR WITH AUTOMATION
   17.2 TO 19.2 HR WITHOUT AUTOMATION

Figure 18.- Reference mission no. 4: Servicing geostationary satellite in situ (TRW, 1984).

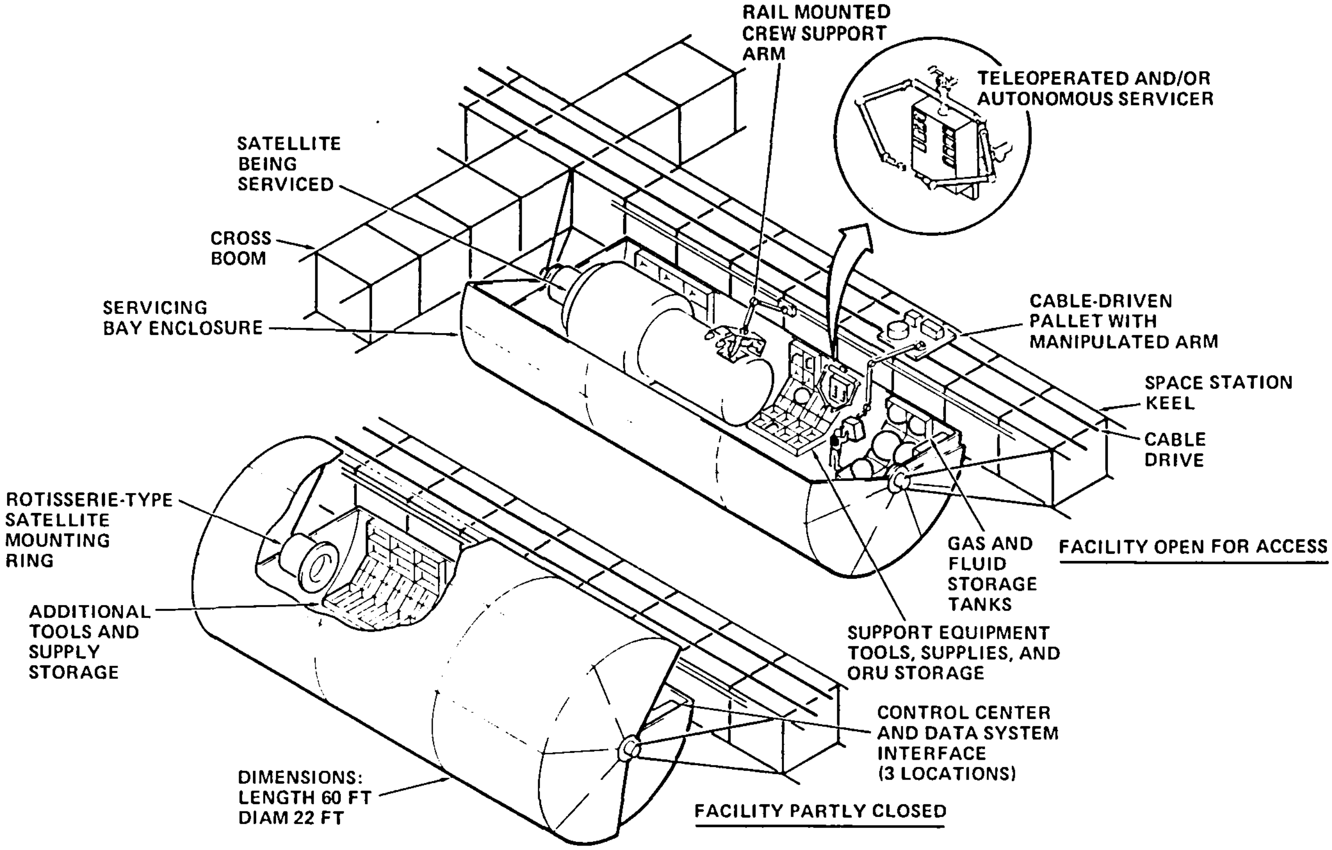


Figure 19.- Enclosed service bay concept (TRW, 1984).

* Major time delay in teleoperation on remote servicing missions can be avoided by scheduling operations for direct line-of-sight contact intervals.

* Geosynchronous satellite servicing demands more reliance on the full robotic mode, with remote human supervisory control and teleoperation being preferably performed from a ground station to avoid intermittency.

* Massive data system support is needed to plan, sequence, and execute tasks and to provide artificial intelligence support to the crew for troubleshooting, failure analysis, and in emergency situations.

* Major spinoff benefits to terrestrial applications will be in the area of flexible/adaptable automation for economical production of small quantities and in advanced data management and information transfer.

OPERATOR-SYSTEMS INTERFACE

Although not a part of the aerospace contractor study group that was contracted to investigate areas of automation and robotics application to the Space Station, Boeing Aerospace Company offered to assist the NASA effort by studying the impact of the Operator-Systems Interface (OSI). OSI is the system of hardware and software that facilitates communication between human operators and the hardware/software system which monitors and controls a functional system. On the Space Station, the functional systems that will be controlled and monitored will include those involved with housekeeping, stationkeeping, and mission and operations planning and scheduling.

The human factors aspects of OSI design lead to the following general requirements:

* The OSI shall be "user-friendly" and shall
  - Provide feedback to the operator

- Provide appropriate level of detail
- Allow different ways for operator interaction

* The OSI shall be multifunctional to minimize power, weight, and volume and to reduce operator workload and error rate.

* Information integration shall be used to reduce workload and error rate.

* Commonality in format and operation shall be maintained.

Space Station constraints on OSI design are given in figure 20.

- VARIETY OF MISSIONS AND MODULES REQUIRES VERSATILITY
- ZERO-G ENVIRONMENT

  - POSTURAL CHANGES
  - LINE-OF-SIGHT FALLS 25 DEGREES BELOW HORIZONTAL REFERENCE
  - HEIGHT INCREASE
  - NORMAL OPERATING POSITION IS NOT SEATED
  - POSSIBLE CHANGES IN QUALITY OF VISION
- DIVERSE BACKGROUNDS OF CREW MEMBERS
- CREW MEMBERS NOT HIGHLY TRAINED IN ALL AREAS
- CREW MEMBERS' ATTENTION MAY BE DIVIDED AMONG MULTIPLE TASKS

Figure 20.- Space Station aspects of OSI (Boeing, 1984).

The Boeing study concentrated on one aspect of OSI, an extravehicular (EV) robot. This was primarily selected because it represented a forward-looking application of automation and robotics technology. Some of the technologies required by a typical scenario of EV robot repair/replace tasks include

* Voice recognition

* Speech understanding

* Natural language understanding

* Machine reasoning

* Image understanding

* Adaptive data base management

* Expert systems

* Learning systems

Figure 21 depicts the Boeing robot design concept which is envisioned to be a free-flying vehicle that will operate outside the Space Station. The robot will be equipped with manipulator arms to hold itself to a work site and to perform physical tasks at a work site. The vehicle would be plugged into a specific berthing port on the outside of the station while being programmed and recharged with expendables. It would be deployed from that port and travel by its own propulsion system near the Space Station to perform its assigned tasks. The primary advantage of the EV robot system is that it would increase crew productivity by reducing the amount of time required for EVA on routine and frequently occurring tasks and by performing tasks that exceed human capability. It would also reduce risks to the crew by performing hazardous functions.

Boeing (1984) also conducted a technology assessment to examine the feasibility of an OSI that would support a fully autonomous EV robot system. They based their assessment on a 3-year, $12 million, international investigation called Transnational Assessment of Autonomous Robotic Generational and Evolutionary Technology (TAARGET). They concluded that it is technically feasible to develop an automated OSI by about 2010 to perform efficient supervisory management functions for an EV robot. The results of this study also show that it is technically feasible to develop an initial, fairly rudimentary EV robot and OSI system by about mid-1990 and a sophisticated, efficient, and convenient system by about 2010. The initial OSI system would have a limited supervisory capability and would be largely experimental in nature. The artificial intelligence technologies that will need to be pushed to develop OSI capabilities are

* Language representation

* Natural language understanding

* Analogical reasoning

* Nonmonotonic reasoning

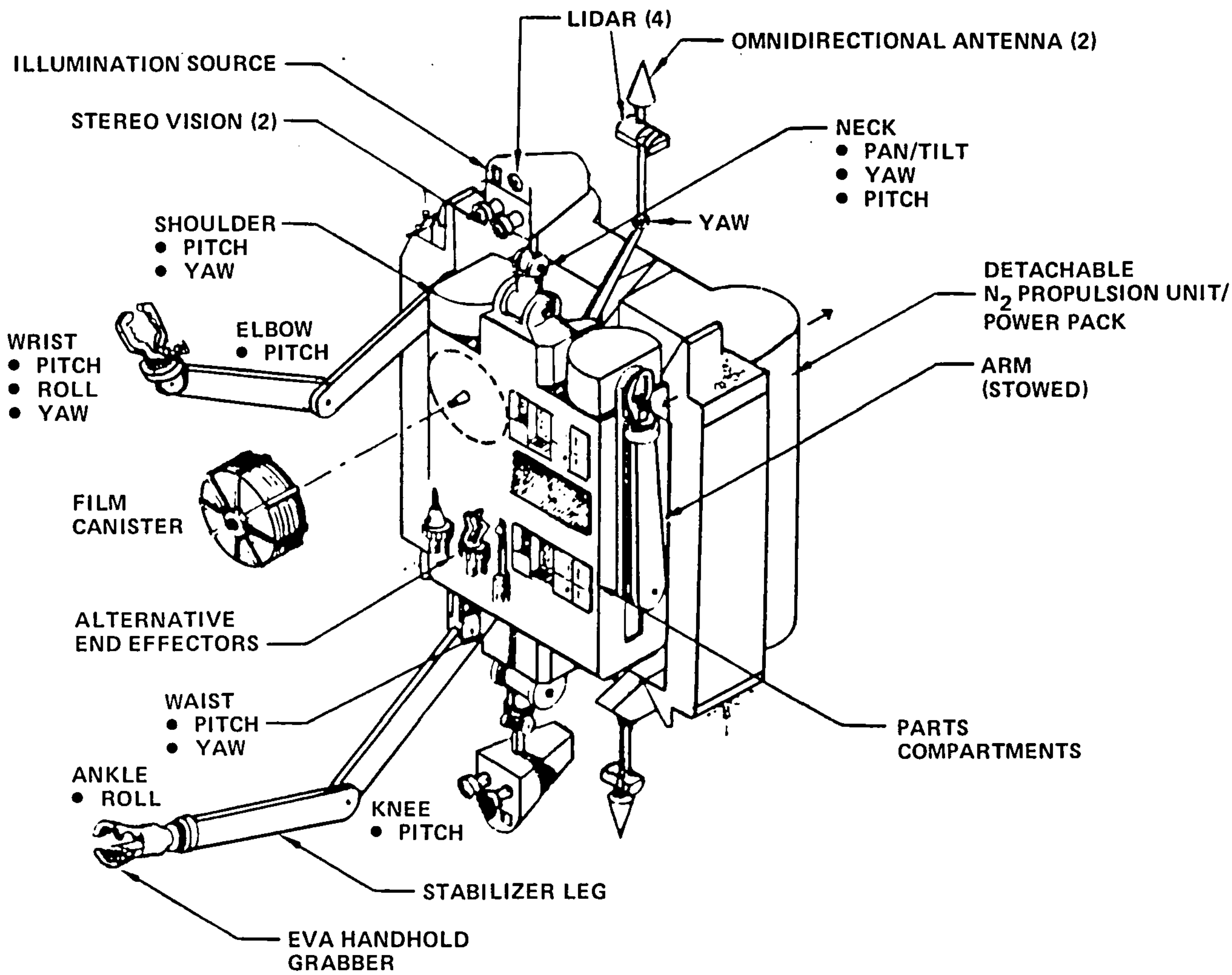
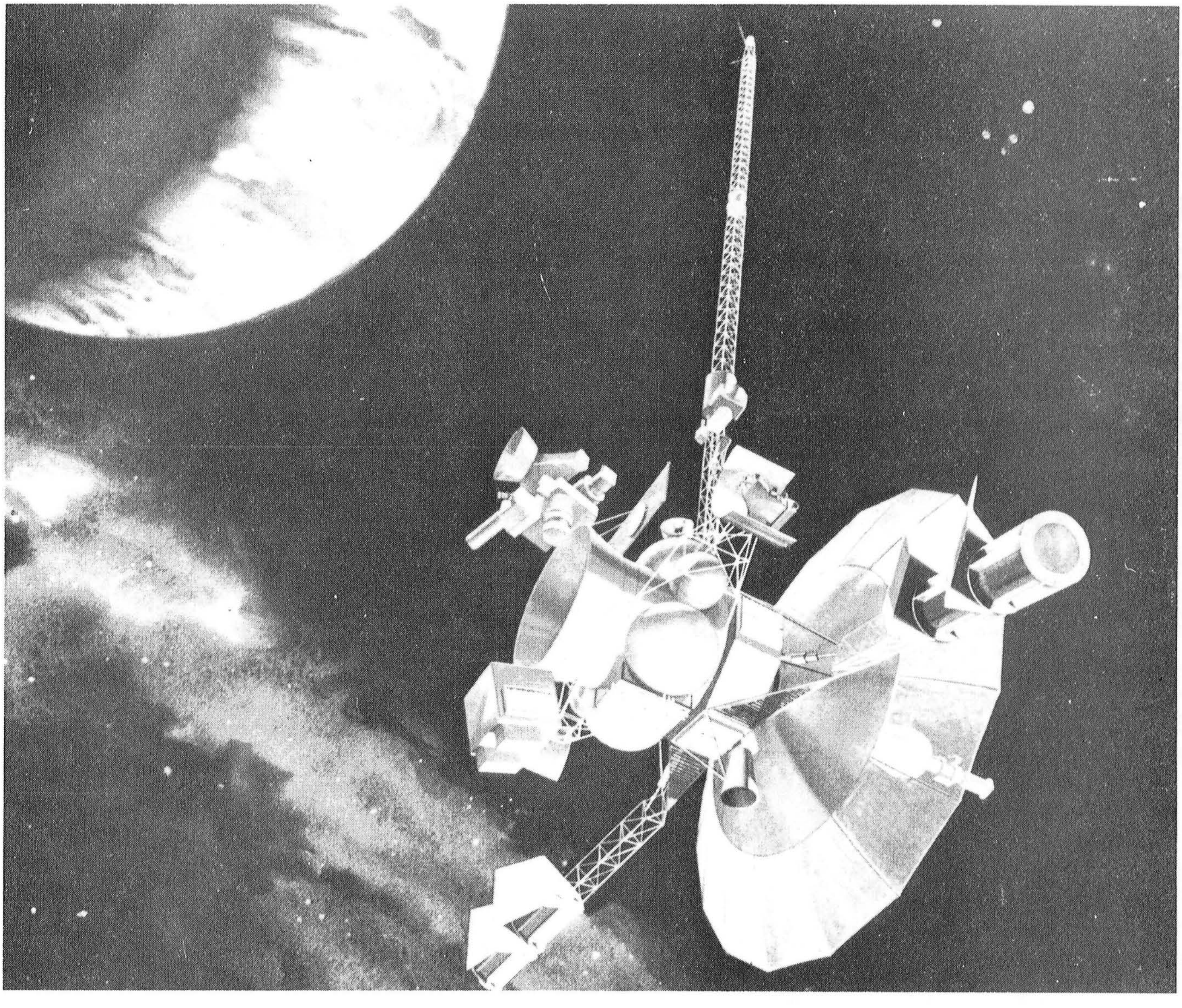


Figure 21.- An external robot concept (Boeing, 1984).



Chapter 6

TECHNOLOGY BASE

In choosing a particular Space Station system or function as a candidate for automation, it is important to define what technology is required to automate that system or function and to assess the likelihood that that automation technology will be sufficiently developed within the time frame specified. To make an assessment of where a particular automation technology will be at some point in the future, it is necessary to define the present state of the art of that technology and then to project it, based on assumptions about the direction of research and progress likely in the interim. When automation of a system or function critical to the evolution of the Space Station cannot be sufficiently developed within the required time frame, then research must be initiated to push that technology. An effective infrastructure is essential to coordinate the incorporation of state-of-the-art technology and the advancement of the needed research to ensure continued advancements in Space Station automation.

The purpose of this chapter is to present major issues concerning the needed technology base relevant to Space Station automation. The chapter reflects these issues and is not intended as a comprehensive discussion of state-of-the-art automation technology. Furthermore, the issues presented here represent a conglomeration of information from many different sources. Much of the information came from a draft of an SRI International review of Automation Technology State-of-the-Art: Anticipated Technology Readiness (SRI International, 1985). Where possible, sources have been identified, but much of the information is presented anonymously. It is not the intention of this report to take credit for other people's ideas, but to present these ideas as an overview of the relevant issues concerning the automation technology base.

STATE OF THE ART

The current state of the art provides the base of automation technology. This base determines what automation can be incorporated into IOC systems now and which research efforts should be pushed to attain the automation goals of IOC and beyond.

Automation technology has been divided into twelve general categories. The present or near-term state of the art is described for each of these categories.

Teleoperation and Robotics

Teleoperation technology is concerned with manipulation and mobility devices whose sequences of actions are controlled by a human operator. Robotics extends the teleoperation technology by automating human manipulation capabilities. In the case of the robot, the sequence of operations is controlled by a computer program as opposed to direct human control. These technologies depend upon manipulator and effector design and control, robot programming, sensing and perception of the environment, and sensing of the robot's internal state.

Manipulator design and control. Manipulation technology consists of a well-developed body of kinematic theory for producing any desired movement of an end effector (e.g., a gripper or tool) carried at the end of a robot arm. The arm may be of any size and shape, but for complete control of end-effector motion it must have at least six independent joints. More joints are needed if the arm itself is also to get around obstacles. Recently, multiple small, three-jointed manipulators have been mounted on a hand to produce true fingers. In the near future we may expect to see the development of extremely small manipulators for confined spaces, and dendritic (multiply-branched) manipulators for complex

manufacturing and assembly tasks. We also expect to see interchangeable effective tools for complex servicing and assembly tasks. We are a long way from having the human operator indicate an end result desired, and the effector carrying out the task with only minimal guidance from the operator.

"Fully general manipulation of an object thus requires that the manipulator have at least six controlled axes or degrees of freedom (DOF's). Typically, these are partitioned into three large-scale-motion axes to provide location and three wrist motions to provide orientation. Commercial robots are usually built with three locational DOF's, giving a total of four, five, or six DOF's. A servoed hand, or gripper - especially if its control is integrated with the arm controller - is often counted as another DOF.

"Very often, a robot does not need to be oriented to all parts of its environment, and relatively few degrees of freedom (DOF's) are required. For many forms of planar or pancake assembly tasks, robots with four DOF's are quite common. Systems with redundant (more than six) DOF's have been built, but the complexity of control and additional manufacturing costs have generally relegated such machines to research institutions, where control issues are studied. Implicit in determining the number of DOF's is the assumption that the robot, being fixed to a support, cannot move. However, the motion of a robot in a plane adds three DOF's to the system, or it can be used to reduce the DOF's in the arm itself. Mobile robots with vision and navigation capabilities have been the subject of much research.

"Links and joints are basically either prismatic or rotational. Three prismatic joints, mounted mutually orthogonally, form the Cartesian configuration. Replacing one prismatic joint (typically the x-axis) with a rotational one, often referred to as the wrist joint, gives the configuration known as a cylindrical robot. Replacing a second prismatic joint (z-axis) with a rotational joint, the shoulder, yields the spherical robot geometry. Finally, a third rotational joint that splits the y-axis into two fixed-length links forms a configuration known as an articulated, or elbow, robot. Robots are commercially available in these as well as other configurations.

"Once we know the robot's configuration and size, we can characterize geometric performance by three interrelated parameters: resolution, repeatability, and accuracy. Resolution, also called precision, is the smallest step size or increment of motion that a robot can perform. A minimum step size is mandated by the digital nature of the control system. Repeatability, or the ability of the robot to return to a previously specified point in space, measures the stability of the robot's internal coordinate system. Accuracy measures how well the robot can conform to an external coordinate system. Currently, repeatability is the most important parameter used in evaluating robots, because most robots move objects between known locations without these coordinates by being led through the sequence of activities it must perform.

"Repeatability performance, in turn, is governed by the quality of the components (encoders, bearings, servos, gears) used in the robot's construction.

"Repeatability is also a function of load and temperature changes. Resolution is primarily a function of the sensors used to measure link lengths or joint angles. The processor used to control the robot somewhat influences this parameter. The ratio of the robot's maximum reach divided by its resolution is often approximately 4000 and since $\log_2 4000$ is approximately 12, 12-bit precision in arithmetic operations is needed. This can be readily maintained on 16-bit processors.

"Accuracy is a function of the robot's geometric precision. When high accuracy is required, Cartesian robots seem to have advantages because there is (ideally) no interaction among the three locational DOF's. Robot accuracy becomes increasingly important whenever off-line non-adaptive programming techniques are used. Repeatabilities of 0.01 mm to 1 mm are typically quoted by robot manufacturers,

depending on the size and intended application of the robot.

"Current robots are basically high-precision electromechanical machines in which mechanical strength and precision geometric sensors are used to provide repeatability and precision. When comparing human and machine performance in this way, the desire is to match the overall ability and dexterity of human performance, not simply to match or exceed one or a small number of strength- or size-related parameters."

"Individual robot joints are moved by servo systems composed of an actuator, position sensor, and servo controller. The three classes of actuators in common use are hydraulic, electric, and pneumatic. Hydraulic drives are available in a number of sizes. Stepping motors, devices that rotate a fixed angular increment given a specified pulse sequence, are used in some robots. The stepping motor eliminates the need for encoders in certain applications because the angular rotation is simply the incremental step times the number of pulses. Problems in detecting overloads or stalls that decalibrate the robot make stepping motors alone suitable for only the least-demanding applications (Jarvis, 1984).

"The newest class of electric drives is the ac servo. The ac servo drives use switching electronics to generate wave-forms that allow ac motors to generate torque at low or zero rotational rates (Keebauch, 1984). Electric motors tend to have speed-torque characteristics not well matched to robot drive needs, so gearing, which generally provides a better match, is often used. Some direct drive motors (Motornetics, Inc.) are now being made that eliminate the need for gearing. High-energy, high-density, samarium-cobalt magnets provide dc motors with torque/weight ratios that may make direct-drive (the stator being connected to one link and the armature connected to the next) robot designs feasible. Direct-drive robots promise both speed and repeatability improvements over geared electric drive robots. Continued progress in developing improved magnetic materials (Robinson, 1984) suggests that motor performance will continue to improve.

"Pneumatic actuators, similar in concept to hydraulic drives, are also in use, offering some of the power-to-weight advantages but without the presence of hydraulic fluids. End effector or hand actuators are usually pneumatic, even on robots with otherwise fully electric drive.

"Designers of robots seem to agree more on position sensors, using predominantly incremental or absolute optical-shaft-angle encoders or resolvers.

"A robot's natural coordinate system is the set of joint angles and link lengths that define its position in space, called (not surprisingly) the joint coordinate system. A world coordinate system consists of the natural coordinates of the three orthogonal Cartesian axes and the three coordinates defining the orientation of the robot end effector. Mapping the robot's internal joint coordinates to the external world's coordinates is the problem of robot kinematics. There is generally no unique solution to this mapping problem. Specifying the preferred configuration is part of robot teaching or programming.

"A third robot coordinate system is the tool system. In this case, the origin and orientation of the coordinate system is aligned with the final link of the robot. This alignment allows natural specification of motion in the direction of the robot hand and in the plane normal to this direction.

"To ensure continuous and coordinated robot motion, we decompose the desired path into a series of short segments used to update the target position of each joint servo at rates of 20 to 100 times a second. For each time interval, we must compute the desired target values from the kinematic solution or an appropriate approximation. Acceleration and velocities are controlled by varying the distance increment between successive points. To allow the robot to move along specified paths, including straight lines, we transform world coordinates into the appropriate joint or link values. By matching the servo response times to the position update rate, we can ensure smooth and continuous motion.

"As an alternative to constraining all six robot DOF's by specifying coordinates, we can use a hybrid force and position mode. The result is called compliant motion. Two examples of the use of compliant motion are the driving of a screw and the turning of a crank. Force servoing is used to insert parts, assemble snap-together components, and follow surfaces (adaptive seam welding is an example of surface following). Obviously, force sensors normally supplement the position sensors normally employed" (Jarvis, 1984).

Robot programming. Robot control requires specifying tasks to be performed by the robot. Each task must be decomposed into a series of motions which, based on knowledge of the internal state of the robot and external state of its environment, will accomplish the desired outcome. To achieve movement, the robot's internal joint coordinates must be mapped to the external world's coordinates. The series of steps to achieve this mapping is accomplished through robot programming and teaching.

"Some features typically available in computer languages for programming robots include interaction with the teach pendant (a device that allows manual control of the robot motion), speed control of the robot, and a variety of constructs that define new robot coordinates in terms of previously taught or computed ones. Languages are normally executed by an interpreter instead of being compiled. The current situation with commercial robots is that each major manufacturer supports a proprietary programming language, with each differing in syntax but not significantly in semantics. Languages suitable for describing tasks naturally are still in the research stage.

"A general problem in robot programming is how to specify robot positions relative to the workplace. Normally, the robot programmer leads the robot through a set of positions using a teach pendant, generally switches or buttons that allow one joint to move or allow motion along one coordinate at a time. Some ability is provided to switch between coordinate systems, to specify speed, or to record locations. Joysticks or other techniques for indicating the coordinated motion of several DOF's simultaneously are seldom used" (Jarvis, 1984).

The current practice in the robot industry is hand coding of adaptive robot control programs by a person skilled in computer programming, robotics, and the particular procedure that the robot is to perform. Tedious efforts that must now be carried out by hand by the robot programmer include

* Constructing a syntactically correct program (several hundred lines to do a task such as remove a screw with a screwdriver)

* Naming dozens of coordinate reference frames and remembering how they are defined in terms of one another

* Measuring distances and angles on the object in order to establish nominal values for those frames in terms of Cartesian coordinates and Euler angles

* Coding data base access requests for the necessary CAD data

Semiautomatic generation of a program using information obtained by interacting with a person skilled in robotics is the subject of much research at present. Isolated parts of the problem seem to be solved, or to be close to a solution. Geometric reasoning, based in part on CAD data about individual part shapes, and automatic planning are important pacing technologies to develop an increasingly automated robot.

Lately, pursuit of semiautomatic program generation is causing a trend away from symbolic programming in a formal robot programming language towards "procedural" programming. In the former, the programmer tells the computer (in a formal programming language with a well-defined syntax and grammar) what the robots should do and how they should do it. In the latter, the programmer operates either simulated robots on a graphic display or the real ones to demonstrate to the computer what is to be done. By menu picks and other simple interactions, the operator helps the computer focus on the significant aspects of what he is doing with the real or simulated equipment.

For example, by moving an arm from one place to another, he might be pointing out a position for a workpiece, describing a tool trajectory, or defining a gripper orientation for grasping a particular object.

External sensors for robots. External sensors provide the robot with its sense of touch, sight, and hearing. (Computer vision will be dealt with in a separate section.)

"Currently, component feeders and subassemblies are located with sufficient accuracy to allow insensate robots to perform the desired tasks. The additional expense required in this mode can easily exceed the initial cost of the robot. Also, much flexibility has been lost because of this special-purpose tooling. These limitations and the obvious costs of building highly precise robots are widely recognized and have sparked the development of sensor-based robots. Already, a few robots are commercially available with simple vision and tactile sensing" (Jarvis, 1984).

Contact, or tactile, sensors may detect touch or measure pressure, force, or torque. These signals must be interpreted and integrated to indicate the nature of the environment to the robot so that the robot can carry out its goals. Contact sensing is one of the two ways that interactions between a robot and its environment can be monitored and controlled. These types of sensors are crucial to dextrous manipulation.

Recently, fingertip-sized sensors have become available that can measure pressure distributions over a planar region about one inch on a side. Such tactile arrays produce a two-dimensional image that can often be interpreted successfully with conventional visual image processing algorithms. Tactile arrays will be very useful in the future for handling small parts, and can be used to identify the parts as well as to determine accurately how the fingers are holding them. A variety of innovative transducers are used in tactile arrays, such as conductive elastomers and integrated circuits.

Tactile sensors either detect when the hand touches something, or measure some combination of force and torque components that the hand is exerting on an object. The term "tactile sensor" means the continuous variable sensing of forces in an array, as contrasted with simple touch, i.e., simple binary sensing at a single point. Tactile sensing implies skin-like properties, with which areas of force-sensitive surfaces are capable of reporting graded signals and parallel patterns of touching. The tactile sensor is used to communicate to the robot system the nature of the object being grasped. Information available from a tactile sensor could include resiliancy of the object being grasped, surface texture, surface normal, bounding outlines, surface curvature, and shape.

Additionally, tactile and force feedback can provide high precision, even in imprecise manipulators, by providing relative movement between the end effector of the robot and the object being moved. This feedback can also detect very small errors in the position of the manipulator by measuring the resultant forces, which can be very large. For example, manipulators with 1 mm open-loop resolution can perform 25 micron operations when under force control.

Although existing commercial tactile sensors are quite simple, having only a few touch elements, promising research is leading to commercial touch sensor devices within 5 years having the following specifications, (Harmon, 1982):

* 10 x 10 elements in 1 square inch
* Sensitivity of 1 gram with upper limit 1000 grams
* Low hysteresis, somewhat nonlinear
* Response time of 1 millisecond
* Robust skin

Until recently, an NxN sensor required NxN output leads to be sent to the processing and analysis device. Recent approaches use some form of multiplexing to decrease the number of wires. In Raibert's touch sensor (Raibert, 1982) each sensor element is

provided with its own computer, and the processed signal is shifted across rows to obtain the output. Some interesting tactile sensors recently reported include

* Conductive rubber (Hillis, 1982)

* Tactile sensing computer (Raibert, 1982)

Range sensors are an important means of determining the location of objects with respect to the robot. In-air acoustic range sensors are accurate to about 1 millimeter over several meters. Laser range finders are accurate to about 1 meter over a kilometer; with a retroreflector on the target, however, they can easily measure to about a millimeter accuracy. A scanning laser ranger has been developed that simultaneously measures the reflectance of an object as well as its distance. This produces precisely registered range and intensity images.

The main drawback to current range finders is that they must be scanned slowly over a scene in order to determine the three-dimensional shape of the terrain and objects. The transverse resolution (beamwidth) of acoustic rangers and the range resolution of laser rangers is too coarse to be useful in many manipulation tasks.

Electro-optical devices that operate in picoseconds are now being developed. These will improve the resolution of laser rangers to the millimeter range without the need for a retroreflector on the target object. Four emerging technologies promise tremendous increases in speed of processing range data and images over present-day electronic silicon devices. These are gallium arsenide, all-optical transistors, Josephson junctions, and optical processors.

Internal sensors for robots. Internal sensors measure internal variables important to the control of a robotic mechanism, or provide information about the systems's well-being. The position and velocity of the joints in a manipulator or locomotion system are examples of critical internal variables used to control movements. Force, temperature, and pressure are often measured in order to assess the internal well being of the system. It is important to sense these variables, particularly for devices that must work for long periods without human intervention, or when no maintenance or repair is possible. Internal sensors are the easiest to implement since they have no direct interaction with the outside environment. One or another of these devices is found on every robotic mechanism.

Proprioception in robotics means sensing the posture of a mechanical manipulator, leg, or other jointed mechanism. This is used mainly in two ways - in controlling the mechanism whose posture is sensed, and in sensing the posture of a teleoperator master arm in order to command the motion of a slave arm.

Proprioception involves measuring the angle of each rotary joint and the extension of each telescoping joint in a mechanism. The joint position sensors are usually either potentiometers, resolvers, or encoders. Today, joint position sensors are accurate enough to enable a six-joint manipulator to place its hand anywhere within a 3-meter-radius working volume with 1-millimeter accuracy. Highly accurate sensors for joint angles or extensions are delicate, expensive, and difficult to manufacture. They are also too large for use in miniaturized robots. In the future, it may prove easier to measure the position of the hand directly than to infer it from accurate measurements of each joint position.

Expert Systems

Expert or knowledge-based systems utilize information obtained from an expert about a particular domain to solve problems in that domain and perform at the level of the human expert. Although there is no definitive definition of an expert system, some of the features distinguishing them from standard application programs are

* Knowledge: They contain a data base of expert knowledge in a specialized area represented in a form that allows some sort of reasoning to be carried out. Most expert systems use a "rule-based" approach that represents knowledge in the form of modular facts and rules.

* Extensibility: The knowledge and the inference engine that makes deductions using this knowledge are kept separate, so that modifications in the rules do not affect the analysis process.

* An explanation system: Many systems can retrace the reasoning sequence used and explain what was done at each step and why. This explanatory capability enables the user to accept or reject the system's conclusions if he disagrees with its reasoning, and aids the expert in debugging the system.

* Incomplete or inexact data: Many of these systems can carry out reasoning processes on incomplete or inexact data.

"The current expert system technology consists of two basic ingredients: symbolic programming and knowledge engineering. Symbolic programming technology includes the fundamental science of symbolic computation, practical techniques for constructing symbolic programming systems, and techniques for building incremental programming environments. Knowledge engineering adds its own three key ingredients: problem-solving engines, knowledge bases, and aids for knowledge acquisition and knowledge-base maintenance" (Hayes-Roth, 1984).

At present, expert systems do not acquire their expertise through experience, but rather are given the needed information and the organization of this information by a knowledge engineer and an expert in the field. Recently the media has paid much attention to expert systems, often claiming these systems as a great cure-all for any problem. It is important to realize, in the face of this "overselling," that current commercial expert systems are effective only in narrow domains of knowledge.

An expert system can be considered as an idiot savant that can deal very effectively with a specialized field, but is incompetent to deal with topics not in this field.

The general categories of tasks that expert systems have been applied to can be broken down as follows:

* Interpretation/diagnosis: This category of expert systems includes those that can accept data from the user about a particular case and, when sufficient information has been received, return a diagnosis or interpretation. Examples of such expert systems include DENDRAL (Buchanan et al., 1978) and two medical expert systems, MYCIN (Shortliffe, 1976), and EXPERT (Weiss et al., 1981).

* Design systems: These are expert systems that may be given particular information and constraints and are required to produce an output that satisfies the given design criteria. An example is R1 (McDermott, 1981), an expert system that designs computer configurations.

* Prediction and induction systems: These systems accept data and look for patterns or other forms of order. When such patterns are found, they can be combined with information about a particular case to predict the most likely outcome. An example of an inductive system is INDUCE, which inferred the relationship between symptoms and disease in soybeans.

* Monitoring and control systems: These systems receive specific on-line data from the sensors on the object being monitored/controlled. These data are rapidly interpreted by the expert system and the appropriate responses generated. In a monitoring expert system, particular ill-defined situations are represented that will trigger specified alarms if they are ever detected. REACTOR, a nuclear reactor monitoring system, and VM (Fagan et al., 1979), a patient monitoring system for intensive care wards, are examples of this type of expert system. YES/MVS, an IBM system, is an example of a real-time expert system used to control an operating system. Often the generation of an appropriate response will require simulation of the expected effects of possible actions on the controlled system.

At present, each system must be developed for its intended application, requiring a significant investment of time and effort. However, tools that can speed the

development process are beginning to become available. These tools range from such automated aids as token completion and spelling correction to line-of-reasoning traces, knowledge-base look-up, and system testing and validation facilities. The first knowledge-based systems have relied on shallow models, but research is underway to provide systems with deep models that are able to model the important interactions within a system. Natural language interfaces will increase the usefulness of knowledge-based systems in some applications.

"In the near future, we can anticipate an emphasis on (1) intelligent instruments that couple data collection with expert data interpretation, and (2) numerous high-value, specialized systems. Over time, these systems will lead to the construction of high-value knowledge bases. Initially, these knowledge bases will have a unitary, self-contained character. Each will employ its own conventions for knowledge representation and will address a specialized problem from one perspective.

"Within a few years, multifunction knowledge systems will emerge. That is, a single system will contain knowledge of benefit to many applications. As diverse bodies of knowledge cooperate to solve a single problem, more heterogeneous knowledge bases and general-purpose knowledge systems will develop. At the same time, these systems will join other technologies, producing integrated automation systems for manufacturing and other commercial activities.

"Both the technology and commercial applications should grow steadily and rapidly through the turn of the century. In the upward direction, user needs drive advances in knowledge systems technology and determine the economic and functional niches the technology will occupy. Specifically, knowledge systems address problems that arise from difficulties in retaining, transmitting, and applying know-how. Knowledge systems provide a means to employ know-how where it is needed, when it is needed, and at great speed. These are the qualities that attract those in factory automation, process control, safety systems, military intelligence, and weapons systems.

"In the downward direction, the field will expand in response to technology pushes. These include improved forms of conventional hardware and software for symbolic computing, less expensive memory and processors, standardized and increasingly reliable knowledge-engineering techniques, and possibly novel non-von Neumann architectures, such as those that the U.S. Defense Advanced Research Projects Agency's and Japan's fifth generation programs now pursue. However, no near-term breakthroughs are anticipated that will affect technology development. Rather, steady improvements in these directions should reduce cost, expand capability, and increase reliability, making an already practical technology much more so" (Hayes-Roth, 1984).

The present limitations of expert systems are of four types - (1) acquisition of knowledge, (2) basic limitations, due to an inability to represent certain situations (e.g., reasoning that deals with uncertain conclusions) or to carry out adequate reasoning processes, (3) "fragility" of the systems, i.e., their inability to deal with anything but their very narrow speciality, and (4) inability to know their limits, i.e., when not to advise.

The following limit the effectiveness of present-day expert systems:

* Knowledge representation: It is important to develop representations for particular domains that are computationally tractable and still capture the important characteristics of the domain, can accommodate qualitative reasoning, and can represent causal models.

* Knowledge acquisition facilities: There is a major problem in obtaining, representing, and debugging expert knowledge about a particular domain. Typically about 5 man-years of effort (using an experienced staff) are required to develop a large system that begins to be robust. Methods are currently being developed for dealing with these problems that should reduce the time it

takes to build new systems; improving the knowledge acquisition ability of expert systems is a major thrust in the DARPA Strategic Computing Plan.

* Reasoning: A major concern of expert-system research is how to use uncertain rules (rules of thumb), so that degrees of belief in individual rules can be combined to obtain a final degree of belief. Since most human reasoning takes place on the basis of uncertain information and weakly supported implications, it is important that expert systems incorporate similar abilities.

* Explanation capabilities: The explanations are usually indications of the solution path traversed in order to achieve the present status, rather than being causal explanations of the type that people usually provide. However, what the user often desires is a causal explanation based on physical reasoning. This type of explanation usually requires that there be a model of the process being discussed. Recent research in medical expert systems uses such models for this purpose.

* Representing procedures: Automatic systems for fault isolation and diagnosis require reasoning about sequences of test and actions. Traditional expert systems, which encode most of their knowledge in the form of rules, are not well suited to representing such procedural knowledge.

* Lack of learning capability: The designer of the system, not the system itself, learns by experience as the system is used. Thus, the designer, not the system, modifies the rule data base. It is a nontrivial task to determine which rules need modification when the expert system is not performing up to expert standards. The designer must consult with the human experts to determine how the rules have to be modified or augmented. The system itself has no way of determining that the user is dissatisfied and no way of automatically correcting the source of the difficulty.

* Need for metaknowledge: The system should have knowledge about the knowledge that it contains - metaknowledge - and be able to use metaknowledge in its reasoning strategy. Such "higher-level" knowledge becomes crucial when large knowledge bases are to be used, since otherwise too much time is expended on unproductive searches and useless deductions.

Planning Systems

Planning will be an important and integral part of many of the functions carried out on the Space Station. Automatic planning has been studied using expert system concepts; however, it is an important area in its own right.

Planning, the determination of a pattern of actions that can be carried out to achieve a goal, can involve predictable actions and their effects (scheduling an astronaut's time) or less predictable situations (sending an autonomous robot to perform a complex task). The potential advantage of automatic over manual planning is that more complex and detailed plans can be generated more quickly and with fewer errors. Autonomous robotic devices require automatic planning to adapt to unpredictable or changing situations by replanning as the need arises. Automatic planning may be done either completely autonomously or interactively with a human supervisor.

Planning systems have not yet achieved the level of performance of the above expert systems. Although several research planning systems have been reported, they have not yet been used in an operational application. Automatic planning is an active subject of research in artificial intelligence (AI).

We encounter two types of planning problems in the Space Station.

* Planning under known conditions: Planning problems that begin with a set of well-defined initial conditions and utilize activities whose effects are known. The problem is to arrange the activities so that the best use of resources attains the best set of goals.

* Planning under uncertainty: Where the initial conditions may not be known beforehand, or the environment is not completely predictable, and it is therefore not possible to initially define the set of situations that will arise. Often only an initial set of "high-level" actions can be defined and the detailed actions are derived as the plan is put into action. Replanning as situations are encountered is often an important part of the process. This type of planning often arises in deciding how to move from one location to another, or in determining what actions are necessary to repair a failed component. One approach that has been used is to develop a hierarchy of plans, each serving as a skeleton for the problem solving process at the next level of detail, (Sacerdoti, 1977). In this way, complex problems can be reduced to a sequence of much shorter, simpler subproblems. One must provide a means, however, for plan modification, since portions of a plan expressed at a high level may turn out to be invalid when expanded on the detailed level.

Both types of planning have been investigated in an attempt to automate the planning process. An automatic planning system starts with a goal or set of goals, knowledge about the initial situation, facts about the world, and activities that can be carried out with an understanding of their effects on the world. The system will produce a plan or partial plan containing specific actions involving specific agents that will achieve the goals. Some planning research is directed toward developing methods for fully automatic planning, such as DEVISER (Vere, 1982), while other research is on interactive planning (e.g., SPOT, ATTENDING, and KNOBS), in which the decision making is shared by a combination of a person and a computer.

In order to develop a plan involving actions, it is necessary to represent the nature and the effect of the actions to the degree of detail required by the complexity of the planning situation. The representation issue lies at the heart of the automatic planning process. A good representation is one that captures the way the action changes the world and what conditions are necessary for that action to be applicable to a particular situation. It is also necessary to model the environment and, in more complex situations, the belief structures and goals of the agents carrying out the actions. Actions can be either deterministic or have some uncertainty concerning their effects. For deterministic actions, the representation must indicate the required conditions (before, during, and after) and the results or effects of that action. For probabilistic postconditions and nondeterminable operators the representation must indicate the probabilities of results that can occur. Because planning is a problem solving activity that involves exploration of alternative hypothesized combinations of actions, a symbolic model of the real world, referred to as a world model, is used to enable simple simulations of the situation to be run as the plans are evolved. As with all models, the world models used in problem solving are abstractions or oversimplifications of the world they model. If a CAD/CAM data base is available, it can be used as a source of descriptions of the world of the Space Station.

Man/Machine Interface

An important area of technology which will be necessary to enable and enhance automation functions onboard the Space Station is that of man/machine interface. Man/machine interface technology is a multidisciplinary area which includes the fields of electronic controls and displays, voice recognition and synthesis, computer graphics, instrumentation engineering, workstation design, and ergonomics. Because the field of voice recognition, synthesis, and natural language understanding is deemed to be critical to the automation function, it is covered in a separate section below.

The various man/machine interfaces within the Space Station will require integrated and consolidated electronic controls and displays to permit the effective human implementation, monitoring, and control of automation-intensive functions. The potential advantages of integrated electronic pictorial displays, generated using color computer graphics, are numerous. This type of display

has proven to be a natural and powerful adjunct to automation in factories, medicine, computer aided design/computer aided manufacturing (CAD/CAM), even our most modern transport aircraft. Using integrated, pictorial displays, the human monitor/operator can be presented with information that can be assimilated much more rapidly and with better situational awareness than can be presented with arrays of electromechanical indicators - the method primarily utilized in the present Space Transportation System (STS). Using consolidated, multifunction controls, as opposed to large arrays of single-purpose controls - a method utilized primarily in the present STS - the human monitor/operator faces a cleaner, less cluttered control panel and one with a natural interface to automated sequences. Applied in conjunction with automation technology, electronic controls and displays have the potential to reduce training and cross-training requirements. This advantage would be provided through use of interactive tutorials in conjunction with knowledge-based systems. Thus, electronic control and display technology has the potential for working in conjunction with automation to provide safer and more efficient operations.

Integrated electronic controls and displays as a means of implementing the man/machine interface have potential for contributing to automation efficiency and safety in many other ways. The new flat-panel electronic display media, for example, are matrix-addressed solid-state devices that have the potential to replace bulky vacuum tube devices (cathode ray tubes). The potential here is for much higher reliability, graceful degradation (as opposed to catastrophic failure), and reduced workstation volume, weight, and power consumption. Advancing computer graphics technology can provide a means of driving the new electronic display media in two-dimensional, pseudo three-dimensional, and in stereo three-dimensional modes that may greatly enhance the effectiveness of monitoring and control modes for a variety of functions such as construction, rendezvous, docking, and proximity operations. The flat-panel displays may be applied in conjunction with emerging microprocessor technology to provide the multifunction controls which may greatly consolidate the man/machine interface and also contribute to greatly reduced weight, volume, and power consumption.

The principles of fault-tolerant hardware and software design (to be discussed in sections below) can also be applied to the man/machine interface as a means of highly automating the interface. Using these principles in conjunction with an appropriate architecture of control, display, display generator, and workstation computer components and associated software, the potential exists for man/machine interfaces that have the same level of fault-tolerance and redundancy as the onboard computer systems which will provide automation functions.

Voice Recognition and Natural Language Understanding

AI research in natural language and speech is aimed at reducing the natural language (or speech) input to a representation in the computer that captures the intended meaning. In "understanding" speech, the input is a digitized acoustic signal, while in "understanding" a natural language, the input is text, usually entered from a keyboard.

While many problems remain to be solved, limited but useful natural language systems are already commercially available. The problem of understanding speech is much more difficult because of signal interpretation difficulties. However, usable technology for speech input has become increasingly available. Subsystems are now available that can "recognize" words, or even sentences spoken by different persons, subject to limitations in vocabulary and sentence construction. Experience with commercial natural-language interfaces to data bases has proved the usefulness of natural-language technology.

Speech coding. *"Speech coding is a set of techniques that transform an analog speech wave to some digital representation, allowing improved use of transmission and storage media. Analog solutions notwithstanding, money can be saved if two or more voice*

channels can be multiplexed on the same pair of wires now used for one channel. New services can be more readily and inexpensively provided if those two wires can handle both voice and data indiscriminately. Systems that incorporate digital speech storage can save both memory and bandwidth by using speech coding techniques that operate at lower bit rates. Will optical fiber obviate the need to compress speech for transmission? Possibly, but embedded plant and other band-limited environments will continue to exist, so speech coding will remain desirable" (Andrews, 1984).

Pulse-code modulation (PCM) is the standard for digital voice transmission in the telephone network. Other techniques of speech coding include adaptive differential pulse-code modulation (ADPCM), subband coding, linear predictive coding (LPC), and multiple linear predictive coding.

"Probably the most important advancement in speech coding products is VLSI. Three years ago it would have been difficult to find linear predictive coders/decoders priced for less than $12,000. Today, we can anticipate coders of greater complexity for far less and can predict rapid and dramatic cost/performance improvements over the next few years.

"Until the early 1980's implementations of LPC voice coders required very smart circuit design using discrete TTL with microprocessors onboard for data management and some high-level decision making. The situation has changed with the development of digital signal processing (DSP) chips. New DSP entries offer higher level language programming and improved development systems, which make them increasingly easier to program. Inexpensive coders/decoders are being offered, and applications are becoming increasingly evident" (Andrews, 1984).

Automatic speech recognition. Automatic speech recognition, ASR, may have reached something of a plateau. Although research in this area accelerated in the late 1960's and continued throughout the 1970's, the goal - the ability to recognize unrestricted vocabularies of continuous speech from any speaker - remains distant and certainly will not be realized until artificial intelligence progresses far beyond its current state.

"Isolated word recognition, as the name implies, requires that a short interval of silence be inserted between utterances. Connected word recognition requires the user only to enunciate each word very accurately. Continuous-speech recognition would allow speakers to use a conversational mode, in which utterances typically run together and the context alters the pronunciation of a word. It is in fact these co-articulatory effects and their variations among speakers that make continuous recognition so formidable" (Andrews, 1984).

Three major issues concern speech recognition researchers: speaker independence, vocabulary size, and isolated versus connected speech processing. Speaker independence is the degree to which the system can recognize speech spoken by arbitrary speakers. While the goal is clearly to achieve complete independence, this has not been achieved. Currently, speaker independent systems support only a very limited vocabulary.

Vocabulary size affects both storage requirements and processing time. The larger the vocabulary the more (fast) storage is required. Moreover, to increase recognition accuracy, more storage is needed for each item in the vocabulary. The recognition process itself amounts to searching the vocabulary and comparing it against the input. The larger the vocabulary, the longer the processing time, thereby limiting its usefulness in an interactive environment.

Isolated word recognition systems have been far more successful than continuous speech recognition. In isolated word recognition systems, each word must be clearly delimited (e.g., by a pause); each word is then treated as an independent entity and is processed separately. Continuous speech requires, in addition, that word boundaries be identified - a complex task that has eluded solution.

Currently, systems are available that operate in real time, recognizing a vocabulary

of about 1,000 words of isolated speech. These systems are speaker dependent, and the amount of training required varies among the systems. Similar systems for recognizing 5,000 words are within the state of the art but not yet available. One of the major problems in such large systems is the long and tedious training sessions. Also, beyond feasibility proof, it is not clear whether applications exist in which such large vocabulary is needed for (the unnatural) isolated word recognition.

Speaker-independent systems exist, but their vocabulary is limited to a few tens of words. It is worthwhile to notice that constructing a speaker-independent system to recognize the (sound of) the alphabet has thus far not achieved sufficient reliability. Thus, spelling out words not in the vocabulary is not a viable option (doing so in a speaker-dependent system with proper isolation is feasible).

A very common application is one that requires recognition of spoken digits. Due to the limited vocabulary (about 150 templates are required) continuous speech digit recognition systems are available (e.g., one by Verbex, Inc.). These systems are useful for inventory control, service and repair, etc.

Interestingly enough, most existing systems are quite insensitive to surrounding noise as long as a single dominant speaker can be identified. This means that speech recognition can be done in the presence of mechanical noise such as in a machine room or inside a vehicle.

The advent of processing technology has prompted DARPA to initiate a new program in speech recognition. The program goals are to achieve accurate, continuous speech recognition for large vocabularies (about 10,000 words). Significant progress may occur in the next decade.

Speech synthesis. In speech synthesis, a computer generates audible words for output instead of printing or displaying the words. Advantages of speech synthesis over printed output are naturalness of communication and the ability to communicate by listening, allowing the person involved to use vision for other tasks.

Two fundamentally different types of speech synthesis systems may be identified - limited vocabulary and unlimited vocabulary. Limited vocabulary systems use prerecorded, typically digitally encoded, speech, often organized as individual words. A computer system determines the order of the words, and a general output capability is achieved, limited only by the size of the stored vocabulary.

Unlimited vocabulary systems take arbitrary text as input, synthesize an acoustic waveform via appropriate algorithms, and output the waveform as audible voice. The algorithms analyze the input text and transform it into one or more intermediate representations, such as a phonetic representation, based on a set of rules. The actual acoustic waveform is derived from an intermediate representation. The major limitation of such a system is that any set of rules will cause mispronunciation when dealing with a large, inconsistent, natural language such as English. To circumvent this problem, most of these systems use an exception dictionary to hold information on the pronunciation of words that are exceptions to the internal rules.

Limited vocabulary systems have been attractive in the past for applications in which relatively small vocabulary size is not a drawback and high speech quality is required. However, unlimited vocabulary systems have recently begun to approach human speech in terms of comprehension if not overall quality. Because of the high level of quality currently achieved by current unlimited vocabulary systems, only small increments of progress may be expected in the next decade in terms of speech quality. However, even current technology is likely to be useful in the Space Station.

Speaker verification. *"Speaker verification is the process of automatically identifying an individual based on voice characteristics. Speaker verification has achieved the same degree of maturity as the other voice technologies we have discussed and could be*

an essential ingredient in many applications. By properly engineering an application using a good speaker-verification technique, product developers can achieve satisfactory performance.

"Verification involves a comparison between a specific utterance of the speaker and a stored reference template of that speaker's utterance. The term verification is used because the speaker would have claimed an identity prior to being verified. Some key-in procedure would be used, and a voice comparison would lead to an accept or reject decision" (Andrews, 1984).

Natural language understanding. Several natural language understanding systems exist today on the market, and all work reasonably within a limited task domain and a well defined context. Thus, query to a data base can be made with a natural language interface where the interface translates natural language sentences into the formal query language and displays the answer. Currently, most natural language understanding systems interface with a single data base. Attempts have been made to construct a single interface to several data bases and have the interface itself deduce which data base to interrogate. Better interfaces of that kind are likely to be available soon.

Performance of natural language understanding systems will increase substantially when new hardware architectures are introduced. At the execution level, natural language understanding requires massive searches and comparisons which can to a large extent be parallelized so that execution time is reduced. The new generation of computers, those consisting of a large number of cooperating processes, is particularly well suited for natural language understanding purposes. It is not inconceivable that specially designed multiprocessors dedicated to natural language understanding will be part of every computing system.

Computer Vision

The most important noncontact sensing mode used in robotics today is vision. The last 25 years has seen much progress in many applications of computer vision, including document processing (character recognition), microscopy, radiology, industrial automation (for example, inspection and robot vision), remote sensing, navigation, and reconnaissance, to name only the major ones.

"The general goal of computer vision is to analyze images of a given scene and recognize the content of the scene. Many types of scenes are essentially two-dimensional. We extract features, such as edges, from the image, or we segment the image into regions, thus obtaining a map-like representation consisting of image features labeled with their property values. Grouping processes can then be used to obtain improved maps from the initial one. The maps can, in turn, be represented by abstract relational structures in which, for example, nodes represent regions among regions. Finally, these structures are matched against stored models, which are generalized relational structures representing classes of maps that correspond to general types of images. Successful matches identify image parts, and give us a structural description of the image in terms of known entities.

"The most commonly used method of 2-D segmentation is based on pixel clustering and classification. In this approach, the scene is composed of flat, uniformly illuminated surfaces of approximately constant reflectivity, giving rise in the image to regions of approximately constant gray level. The regions' gray-level ranges can be determined by examining the images's histogram (a bar graph showing how often each gray level occurs in the image); regions of constant gray level give rise to peaks on the histogram. The image can thus be segmented into regions by finding gray-level ranges, each of which contains just one peak; the sets of pixels lying in each range thus define a segmentation of the image.

"In other situations, notably in robot vision applications, the scenes to be described are fundamentally three dimensional, involving substantial surface relief and object occlusion. Successfully analyzing images of such scenes requires a more elaborate

approach in which the three-dimensional nature of the scenes is taken into account. Here, the key is to infer the surface orientation at each image point. Clues to surface orientation are derived directly from shading, or gray-level variation, in the image. Alternatively, two-dimensional segmentation feature extraction techniques are first applied to the image to extract such features as surface contours and texture primitives, and surface orientation clues are then derived from contour shapes or from variations in texture. Using the surface orientation map, we once again apply feature extraction and segmentation techniques to yield a segmentation into visible parts of bodies or objects. These in turn are represented by a relational structure. Finally, the structure is matched against models to yield an interpretation of the scene in terms of known objects. The matching process is more difficult in the three-dimensional case than in the two-dimensional case because the image shows only one side of each object, and objects may partially occlude one another. We are not simply "matching" a model with the observed structure, but rather are verifying that the model could give rise to that structure under appropriate viewing conditions. Given images taken from different viewpoints, a three-dimensional model of the scene can be constructed directly, using stereomapping techniques.

"An important method of 3-D shape recovery is based on analysis of the gray level variations (shading) in the image. A uniformly illuminated curved surface of constant reflectivity in the scene will give rise to a region of varying gray level in the image, since the brightness of the surface at a point depends on its orientation relative to light source and viewing directions. The 3-D shape of the surface is not uniquely determined by the shading, but shading strongly constrains it, and under some circumstances, we can infer a plausible shape solely from shading information.

"Information about the 3-D shapes of the surfaces that appear in an image can be used to segment the image into regions that correspond to surface sections, rather than into regions of uniform brightness.

"Matching with a 2-D model involves measuring properties of and relations among the regions or features in the image, representing this information in the form of a relational structure, and matching this structure to stored models, which are generalized descriptions defining object classes. Even in two dimensions, such models are often very difficult to formulate, since the constraints on the allowable property values and relations are hard to define.

"In three dimensions, the problem is rendered even more difficult because only one side of an object is visible in an image; the image description is 2-D, while the stored object models are presumably 3-D, object-centered representations. Matching with a 3-D model involves using the structure derived from the image to define constraints on the objects that could have given rise to the image and finding object models that satisfy those constraints" (Fu et al., 1984).

Suppliers of vision systems include Machine Intelligence Corporation, Automatix, General Electric, and Bausch and Lomb. These systems can identify and locate objects in a controlled environment with the following restrictions:

* The number of possible objects that can be identified is limited.
* The number of objects in the scene is limited.
* The objects do not overlap.
* The object is always viewed vertically.
* The image features of an object are extracted from its binary image (silhouette).
* The objects are illuminated so as to obtain high dark-to-light contrast.

Typically, a system is trained to distinguish among objects by showing it sample objects. It will find outlines of each object and, using various techniques, develop a classification so it can distinguish the different types. In general, research in this area will lead to more

flexibility in the images that can be processed, including the following capabilities:

* Identifying objects that overlap

* Accommodating for a change in perspective

* Fewer requirements on lighting conditions

"*Most successful applications of computer vision have involved relatively simple domains and have been primarily two-dimensional. For example, in robots vision, systems that recognize parts on a belt (well-illuminated, nonoverlapping, in specific 3-D orientations) are not hard to build, but systems that recognize parts in a bin (shadowed, overlapping, arbitrarily oriented) are still in the research stage. Existing techniques will in principle handle such complex situations, but they need to be refined and tested extensively before they can be used in practice*" (Fu et al., 1984).

For robotic applications, solid-state cameras are preferred over those with vacuum-tube imagers such as vidicons because of their ruggedness, low image distortion, low power requirements, and small size. Today's solid-state television cameras can operate on either visible or infrared light. The highest image resolution available (800 by 800 pixels) is now about twice that of broadcast television, and the fastest cameras can take 2,000 pictures per second (as compared to 30 for broadcasting). Nondestructive-readout cameras can store an image for hours, and the image can also be modified by a computer while it is stored. Within about 10 years, 2,000- by 2,000-pixel resolutions should be available. But, to reduce the amount of image data to be processed, some cameras may have only a small high-resolution region near the center of their field of view ("foveal cameras").

An interesting class of vision sensors is the "eye-in-finger" approach. A linear array of light transmitters and receivers indicates when the light beam is broken by an object that is between the fingers. A two-dimensional binary image is obtained by moving the effector. Three linear arrays are used, one on each side and one on the bottom. This type of sensor could be useful in directing mechanical fingers in grasping an object.

Relational Data Bases

There exist three major types of data base management systems: the hierarchical or tree model, the network or link model, and the relational model. The latter is the newest approach and a dearth of commercially available systems may be partially explained by the necessarily large amounts of computing power and storage required, which, in the past, have been generally unavailable and/or expensive. However, in the case of the hierarchical or network models, for a large and complicated data base the schema and the manner in which users may access it may become very complex. The relational approach strives to avoid many of these drawbacks. It views the logical data base as a simple collection of two dimensional tables called relations. The columns of the table correspond to the data items and the rows to the logical records. The tables are easily understood and handled by users with little or no training in programming, and involve no consideration of positional, pointer, or access path aspects.

These tables are formally a mathematical set and can be manipulated by relational algebra procedures, such as JOIN and PROJECT. JOIN links two tables based upon a specified data item from each. The result is a third table containing those rows where a Boolean condition (e.g., equal) between the specified data items is satisfied. PROJECT extracts columns from one or more tables and creates a new table containing a subset of the original(s) based upon a Boolean condition. Using these and other set operations, it is possible to manipulate or extract any information in the data base.

Besides being easy to understand, another major advantage is the ease with which the data base can be changed. This holds true not only for adding and deleting records but also for creating new tables, adding columns, etc. It is also easy to ask a relational data base new and unusual questions, because anything

can be related to anything else and all the data are accessible from any point.

In order to support automation, as much data as possible describing the design of the Space Station must be captured in a machine-readable format in a permanent Space Station design Data Base. These data include motivation for elements of the design, indication as to how parts are assembled and disassembled, cautions concerning the handling of objects, etc. Although it will not be immediately useful, the availability of these data will be absolutely crucial in the future when artificial intelligence technology evolves sufficiently to allow a computer to understand it. It will then be useful in a wide variety of automation on the Space Station, including automatic guidance of robots, equipment monitoring, malfunction detection, diagnosis, and the planning and execution of repair procedures.

The information must be captured as it is developed. This will be relatively easy to achieve in the case of computer-aided design data. However, it will also be necessary to get the designers to supply written descriptions of the reasons for their design choices and, where relevant, how the equipment in the designs is supposed to operate. Most difficult of all will be to capture information from engineering drawings that are not produced with a CAD system. Either the drawings must be scanned and the compressed facsimile data stored, or the original paper records must be safely archived and indexed for later scanning.

Distributed Processing

There are two distinct types of distributed processing required for the Space Station which are characterized by different requirements and implementation hardware. Onboard systems are characterized by heterogeneity, specialized computing requirements, and the need for flight-qualified hardware. Ground systems are expected to use high-performance commercial machines in a much different computing environment involving large distributed data bases and shared computing resources.

Onboard distributed processing. The onboard system will have a hierarchy of computing tasks from overall system control and autonomous maintenance functions to dedicated computers embedded within spacecraft subsystems and high-performance general- and special-purpose processors for processing data from various experimental payloads. It is likely that different processor configurations will be needed at different places in the system and the embedded nature of many processors will necessitate specialized interconnections and dedication of functions to specific processing sites.

For onboard distributed systems, as with any new technology, a learning curve is involved in their development. The Johnson Space Center has instituted an architecture study, conducted by the C.S. Draper Laboratory, for the development of a fault-tolerant distributed processing system for the Space Station. The Galileo project at the Jet Propulsion Laboratory will employ distributed processors on a spacecraft. This system can autonomously generate commands onboard for spacecraft control and handling of unexpected faults. Also the Air Force has developed distributed onboard processing systems. Through these and other projects, a limited knowledge base of project management, system architecture, integration, testing, and of parts procurement and development has been developed within NASA. However, the Space Station will be much more complex than any onboard distributed system of the past and a number of important research and development issues must be addressed long before systems of this complexity are constructed.

Ground-based distributed processing. It is expected that ground-based processing will make use of local area networks that are commercially available and that maintain the integrity of large data bases. Technology of this type is being developed, a good example being the LOCUS system developed for DARPA at UCLA. Systems of this type have the following characteristics:

(1) For high availability, a consistent name space is used for files or objects throughout the distributed system, and

the system is made to appear homogeneous. Objects can be reached from more than one computer in the system so that if one machine fails it is possible to switch to another computer and continue the computations. All objects paged to disk are transparently stored at two different sites so that if any storage site fails (i.e., its host computer or peripherals) the information remains available.

(2) Data Integrity depends upon detecting faults before fault-damaged data is written to the disks. In current systems this depends upon the fault-detection capabilities of commercial processors which are reasonably good but by no means comprehensive. A number of transient faults may occur and go undetected. Techniques should be developed to improve fault diagnosis in the ground processors if an occasional corruption of data bases cannot be tolerated.

Fault-Tolerant Processing

Fault-tolerant computing implies the development of computing systems which can continue correct computations in the presence of faults. As systems become more complex the probability of failures increases. Current space programs have been especially concerned with "single event" upsets which are transient disturbances which can create errors in memory and prevent and/or invalidate subsequent computations unless prompt recovery intervention takes place. Less frequently, components will fail, requiring redundant hardware to restore proper operation. Spare components are included in the design along with automated fault diagnosis and recovery mechanisms.

A number of fault-tolerant machines have been implemented and this can be viewed as a relatively mature technology. NASA has been the leader among government agencies in the development of fault-tolerant computing. Three basic approaches have been employed in both the NASA and other fault-tolerant computer designs. The first (triplication with voting) uses groups of three computers which simultaneously perform identical computations. Their outputs are voted to mask the effects of a fault in any single machine. These massively redundant and relatively expensive approaches have been employed for critical applications such as aircraft control. A second approach is to operate computers in pairs and compare their outputs to detect disagreements. If a disagreement is detected, a diagnostic program is run to find the faulty machine. This approach often fails for transient faults because both machines will pass a diagnostic, but the machine which had the transient fault may have undetectably damaged information in memory (so the two machines will continue to disagree when restarted). The third approach uses self-checking computers, i.e., computers which are designed with internal checking logic and which can detect their own errors during normal operation. It has been shown that a computer can be made to be self-checking with an additional complexity of about 10 percent. For noncritical applications, a single self-checking computer is powered with one or more unpowered backup spares. If the active machine fails, the spare is powered and the computation is restarted. For critical computations, two self-checking machines perform the same computations. If one fails, a spare is substituted for the faulty machine. The other machine initializes the newly activated spare machine and a configuration of two machines is reestablished. Self-checking computers were developed for long-life deep space missions. They require less power and provide longer life for a given amount of redundancy than does the triplicated approach.

Computer Technology

By the time the Space Station becomes operational, VLSI circuits of capabilities similar to VHSIC phase 1 devices should be available for use. Single chip processors are expected which will be capable of executing up to several million instructions per second, and it will be possible to fly much larger memories than is currently possible. It should also be possible to develop custom chips with complexity equivalent to 40,000 gates and clock speeds of from 20 to 40 mHz. It is expected that these custom chips will be used

for circuits of two basic types. Building block chips will provide standard communications interfaces, fault-tolerance support, and other functions used repeatedly in connecting the various processors into the Station's distributed computing system. Custom chips will also be needed for preprocessing very high rate payload data.

Software

Software includes programming languages, operating systems, and software engineering methods and tools (Reference NASA TM 85631, NASA Computer Science Research Program Plan, March 1983).

In scientific and engineering fields, FORTRAN is, and will continue to be, a primary programming language. More and more "Fourth Generation" languages are appearing which provide easier user interface to data bases, spread sheets, and other business applications. For embedded systems, which will exist on the Space Station, the DOD Ada language is becoming a standard. Much effort is currently being expended in developing Ada compilers, run-time systems, and support environments. Special-purpose languages for list processing and artificial intelligence applications include LISP and PROLOG. These languages are also being refined and standardized.

Primary drivers in the development of modern programming languages and applications generators are cost-effective development, maintenance, and reliability. If computer programs can be written more automatically, then there is less chance of human error, meaning more efficient code development (cost effective) and fewer mistakes (reliability). Also, if programming languages are standardized, then programs (such as subroutines, modules, and packages) can be exchanged and reused on different computers for different applications. Again, this increases the reliability by employing well-used software components and reduces the cost of developing code.

Software reliability techniques have been suggested, including N-version programming and recovery blocks. Such techniques are used in cases of critical software where high reliability is required. However, the effectiveness of these techniques is not yet proven, and additional research is needed.

High-level programming languages, debugging tools, and operating system utilities have improved both the productivity and reliability of software development. However, the process of describing software requirements and converting these into object code still involves many manual steps, prone to human error.

Information Networks

Information networks will provide for the distribution and communication of information and data throughout the Space Station in support of the distributed subsystem functions and processing. With the emphasis on inclusion of high degrees of automation and robotics in the Space Station, the anticipated data networking poses complex technological requirements. Preliminary investigations have established three primary requirements for a space station information system.

* High performance: Real-time video, image processing, station maintenance, spacecraft rendezvous, and proximity operations will require data distribution at rates exceeding 108 bits per second.

* Reliability/fault tolerance: The integrity of the Space Station and the lives of its personnel will depend on continuous and reliable distribution of data for monitoring and control of the Station.

* Extensibility/modularity: As the Space Station expands and its emphases change, the information system must evolve gracefully.

It is believed that one or more networks will be capable of simultaneously providing the necessary data communications and computation capacity, fault tolerance, and modularity. Many network types are being developed for commercial and industrial use, and much research is being conducted in university and industrial laboratories. Ethernet, which is a linear bus-type network,

is the most mature commercial/industrial Local Area Network and possesses the extensibility/modularity requirement, but does not possess the high-performance and fault-tolerant requirements. Hyperchannel is an example of a high-performance network with extensibility but does not have any fault-tolerant attributes. These are research efforts on fault-tolerant networks being conducted (Ohio State, C.S. Draper Labs), and these networks have the extensibility requirement but lack high performance. The concept of an integrated network approach where video, voice, and data are simultaneously served is being researched by Bell, but at this time is still relatively low performance. The high-performance requirement will best be served by the use of fiber optic and integrated optic components and devices (i.e., optic node), and the fault-tolerant requirement will best be met by the selection of a mesh architecture or topology that would provide simultaneous or alternate data communication paths. Currently, there does not exist a commercial, industrial, or research network that simultaneously possesses the high performance, fault tolerance, and extensibility requirements. NASA has undertaken technology to develop information networking that simultaneously meets these requirements.

RESEARCH RECOMMENDATIONS

To ensure the evolution of an automated Space Station, research must be focused on those automation technologies which directly fulfill the needs of the Space Station. The following recommendations for research efforts emphasize these needs. They are also broken down into the same twelve categories used in the previous section.

Teleoperation and Robotics

NASA research in teleoperation being supported at OAST must be expanded in order to have an impact on the Space Station. In particular, work is needed in effectors, sensors, control systems, teleoperation procedures, teleoperation workstations, and sensory feedback techniques. Current earth-bound robots are not equipped to deal with the new and hostile environment encountered in space. Zero gravity will introduce complex kinematics/ dynamics problems, and allow the robot to exploit novel forms of locomotion not feasible on Earth. Problems involving thermal gradients and radiation must also be researched to ensure that a robot will be robust in the space environment. The adequacy of these research results can be partially tested in neutral buoyancy tanks, but true adequacy can be determined only by experiments in space.

Some important research topics for manipulators are as follows:

* Design of manipulators: Zero gravity will allow manipulators to be longer and thinner than conventional industrial models, some of which are so bulky as to resemble machine tools. However, there is currently no adequate theory for controlling a manipulator which has flexible, limber links between its joints. This will limit the slenderness that can be achieved with available materials. Light, stiff materials such as carbon fiber composites, or even titanium, may be cost-effective in a space manipulator. Research in actuators should concentrate on improving power-to-weight ratios and energy efficiency. A possible starting point is the remotely operated vehicles (ROV's) now being developed for undersea work platforms. Many of the repair and inspection tasks for offshore oil platforms and undersea pipes are similar to those in space. Another similarity is the use of lightweight arms (because of the buoyancy of the water).

* An adaptive robot arm: Other things being equal, it will probably be advisable to trade off accuracy and repeatability to obtain finer resolution in designing an adaptive robot arm. The external sensors allow closed-loop control that compensates for the lack of those characteristics. This approach also compensates automatically for wear, minor structural deformation, and other kinds of performance degradation that may result from extended operation.

* A general-purpose hand: Much research is needed in understanding the control

techniques of a multiple-fingered hand using nine or more degrees of freedom.

* Robot repair of robots: The AEC at Oak Ridge has developed robotic arms that are modular, so that one arm can replace the portion of a failed arm of another. This type of arm design would be important for space teleoperation.

* Wrist socket interface: A standard design for a wrist socket interface would be extremely useful. It should perform the following functions:

  - Provide strong mechanical support for the end effector (hand, tool, sensor, etc.)

  - Protect the end effector against excessive force and/or torque in any direction. For example, it might allow the end effector to break away from the wrist, triggering shutdown of the arm. The end effector should still be retained, for example, by a tether.

  - Protect the arm - e.g., by allowing the tether to separate under excessive tension

  - Automatically return the end effector to its normal position after breakaway when the excessive load is removed

  - Allow quick connection and disconnection

  - Interchangeability of special tools

  - Transfer power to the end effector

  - Transfer information to and from the end effector

  - Transfer fluid (air, hydraulic fluid, propellant, etc.) to and/or from the end effector

* Task mechanics: The least developed, and perhaps most important, component of dexterity is knowledge on the part of the manipulation system of what will work. Very little is known about how parts interact and how a hand can interact with a part. Strategies and tactics for manipulation are needed that will reduce the number of conceptual degrees of freedom in an assembly problem so that it can be solved. Primitive manipulation operations must be developed that will permit sophisticated actions with reasonably straightforward generation schemes. Preliminary progress in this area points the way to controlling uncertainty without resorting to sensing. Recent work has begun to address the fundamentals of task mechanics, and industrial practitioners have amassed substantial experience, though most of it has not been codified. Research in this area, if adequately emphasized and supported, will have the most important impact on improving robot dexterity.

There has been little research in the analysis of touch sensor pressure patterns. Of great importance is the time sequence of these patterns and their analysis. Other research topics include development of space-rated touch sensor integration. Also important is the incorporation of sensor information into automatically produced plans. Other noncontact sensing applications to be looked at include acoustic, chemical, and temperature sensing.

Sensor-based control is a particularly important area. In terms of manipulation, the ability to use data from sensors that move with the hand is both crucially important and very difficult. Except for force-sensing wrists, little has been done in this area. Fundamental and development work are both required.

Mobile robots will be essential on the Space Station. Robot mobility can be improved in three respects - sensing, control, and design.

* Sensing: The problem of providing a mobile system with information about where it is, the direction of its motion, and the speed of its motion are very important. While this problem is common to a variety of mobile technologies, the bandwidths, needed for legged systems as we currently envision them, are particularly severe.

Satellite-based systems will probably not provide the kind of fine-grain information needed. Specialized techniques may prove acceptable in specialized environments. The single most important barrier to achieving useful mobile systems that do not have direct human control will be the task of determining the detailed shape of the terrain along the paths of interest. This problem involves sensing, perception, and spatial representation. The difficulty of this problem is related to the generality of the situations in which the system will be expected to work. The speed of locomotion may also be a factor.

* Control: Most current autonomous vehicle research deals only with flat floors. Solutions to most problems on flat floors are within sight. Research is needed to find techniques that will provide mobility where the terrain is not flat. Even with complete knowledge of the terrain, there are substantial control and planning problems that must be solved before mobile systems will negotiate difficult terrain. Solutions to this sort of terrain problem will involve the mechanics of locomotion, control, planning, and heavy doses of geometric representation and reasoning. While medium-grain knowledge of the terrain will be important, so will techniques that make a system inherently insensitive to minor variations. Substantial mechanical design of new mechanisms will be involved in building systems that can negotiate rough terrain.

* Design:

  - Self-contained power: Mobile systems will need to provide their own power. While it does not appear to be too hard to carry a power supply at large scale, say gross vehicle weights in excess of a ton, this is a very hard engineering problem at smaller scale, say human size.

  - Optimize payload, range, and speed: If a locomotion system is to be a transportation system, it must carry a payload, and the distance that it must carry the payload without intervention is of considerable importance. The speed of transport is also important. Part of the payload, like computing equipment, communication equipment, fuel, etc., may be needed for locomotion. It will usually be desirable to transport something that is not a part of the locomotion system itself, like a pair of manipulators or a sensory system. Consideration of these factors is an optimization problem for the system architect and the mechanical designer. Special control strategies may also be important.

"*Robot programming languages are also in need of concentrated research. Needs include task-level programming to incorporate planning, the automatic decomposition of tasks into subtasks, and the accommodation of other features often found in AI-related projects. Also, robots need procedures for automatic and general-purpose error recovery. In spite of the need for advanced features like task-level programming, programming language for robot motion that is both conventional and standard would greatly stimulate progress in these areas*" (Jarvis, 1984).

Expert Systems

Research in expert systems should be focused on the special needs of the Space Station in maintenance and control of Space Station subsystems and manufacturing processes.

The representation of knowledge is a key issue in expert systems, since the representation forms the basis for reasoning and explanation. The representation chosen depends on the nature of the application.

Important questions to be studied include

* How are elements of one body of knowledge related to one another?

* How can reasoning about space and time be carried out?

* How can one represent knowledge for use in determining the causes of events; i.e., how can one represent causal models?

* How can one represent "knowing by doing" procedural-type of knowledge, i.e., heuristic information about what to do and how best to do it?

The end product would be both general-purpose and application-oriented knowledge representations suitable for various Space Station applications.

Research in knowledge representation should be carried out in the context of both specific Space Station applications and general representation issues. Thus, knowledge representation would be developed for each class of expert system applications, such as maintenance, repair, control of subsystems, and man/machine interaction. It is expected that maintenance and repair will require representations that are strong in causal explanation, that control subsystems will require representations that have a fast response, and that man-machine interaction will utilize representations capable of providing various levels of explanation. Much research needs to be done in real-time expert systems.

The ultimate goal is to allow an expert to encode his own knowledge directly without the need for a knowledge engineer, to refine that knowledge, and to verify the correctness of the knowledge base. The expert system would suggest possible modifications and handle "bookkeeping" functions.

The following research tasks would be appropriate:

* Initial knowledge acquisition: Since much of the role of the knowledge engineer is to aid in the structuring and formalization of the problem domain, it is not clear that this can be done automatically. An appropriate research task would be to develop a menu of models that would be useful for a particular class of applications. The expert, in a dialogue with the system, would select the most appropriate data structures. It is expected that natural language interaction might be important here.

* Knowledge verification: The builders of a knowledge-based expert system must ensure that the system will give its users accurate advice or correct solutions to their problems. The process of verifying that a system is accurate and reliable involves testing and refining the system's knowledge in order to discover and correct a variety of errors that can arise during the process of transferring expertise from a human expert to a computer system. An automated assistant for knowledge-base debugging has been used in the ONCOCIN system. The automated assistant checks for inconsistencies and gaps in the knowledge base, helps the experts and knowledge engineers to communicate with each other, and provides a clear and understandable display of the knowledge as the system will use it. This research task would develop a similar assistant for knowledge-base debugging.

* Knowledge refinement: An important tool for refining a knowledge base is a facility for displaying the existing base in some graphical or structured manner. This task would develop tools for interacting with an expert to indicate gaps in the data base for which knowledge or procedures should be supplied.

It is important to be able to reason based on incomplete or uncertain evidence. Research in this area would provide techniques suitable for such reasoning focused on specific applications. This research would investigate techniques in Bayesian reasoning, evidential reasoning, fuzzy reasoning, and nonprobabilistic approaches (e.g., truth maintenance) to find those that are appropriate for the Space Station applications.

There are various kinds of explanation that might be provided in an expert system:

* What is the immediate goal?

* What is the justification for an action?

* How will a particular action contribute to the goal?

* Why is that a good choice of methods to accomplish the goal?

The end product of this research would be techniques for supporting various types of explanation. This research task would examine existing explanation systems, choose those that are appropriate for the various applications, and develop new explanation systems. It may be necessary to develop special representations for domain-specific applications.

Most expert systems are not well suited to problem domains where much of the expert knowledge is procedural and where tests and actions need to be carried out in a particular time order. Yet, this is exactly the type of knowledge that is common to the problem of fault diagnosis in complex spacecraft systems. This research task would develop procedural expert systems that explicitly represent procedural knowledge while still retaining the benefits of traditional expert systems. The basis of the scheme is to use a representation that is sufficiently rich to describe arbitrary sequences of actions in a simple and natural way, while at the same time to avoid explicit procedure "calling." Schemes for explicitly representing and using expert knowledge of a procedural kind must be developed to bridge the gap between the procedural and declarative languages. In addition, the representation of temporal domains needs to be properly formalized, and suitable techniques for truth maintenance developed.

Research needs to continue on symbolic processors that are capable of dealing with the types of symbolic manipulation often found in AI applications. There is no reason to expect that the addition of incremental amounts of knowledge will lead to global understanding. To be able to understand, the system must be able to generate higher level concepts by comparing and generalizing problem situations or groups of knowledge elements. No such ability has been provided in existing systems. This ability to make comparisons and to determine similarity is a crucial part of generalization and learning. A learning expert system would be one that learns from experience, similar to the way a human expert broadens his knowledge with experience. This is a very difficult research area. An initial project might be an interactive scheduler that learns as it is guided.

Planning Systems

Planning systems have additional research needs. There are difficult problems in representing time and space for automatic planning. While people have little trouble in dealing with time and space parameters, it is difficult to formally represent the implicit time and space relationships that exist in a situation in a computationally effective form. This research is needed for automatic planning in general.

Space Station representation research should be focused on representing the objects and their relationships as well as how the world of the Space Station is affected by actions. One must somehow indicate the properties of objects in this world that are important to actions, such as movability, danger, hardness, etc.

Interactive planning research should focus on the development of a Planning Assistant for use by the astronauts. A major focus is on suitable man/machine interfaces such as high-resolution graphics displays.

An important part of the planning process is using portions of the previous plans to solve a current problem.

Planning under uncertainty is one of the most difficult of the research areas, but is most crucial for autonomous operation of robots and vehicles. Some of the current DARPA research concerning planning for an autonomous land vehicle, and work in autonomous robots at Carnegie-Mellon University, Stanford University, and SRI International will be pertinent here.

Realization of the full benefits of multiagent systems will require research advances in the reasoning abilities of the individual agents and in interagent coordination and communication strategies. For multiagent planning, it is necessary to carry out research in models of actions, belief of agents, and communication among agents.

Man/Machine Interface

Although much technology is becoming available in the area of man/machine interface, there are many remaining research problems. In the fields of electronic display media, computer graphics, and workstation design, the thrust of most R&D efforts is aimed at industrial and commercial applications. These applications, in most instances, do not have the stringent visual performance requirements and certainly do not have the physical constraints (weight, power, and volume) that the Space Station application will entail.

Research is needed to develop appropriate display media, computer graphics, consolidated controls, and workstation design technology. In the field of display media, flat-panel display technologies require development to overcome present limitations on screen size, uniformity, resolution, luminance efficiency, and color capability. In the field of computer graphics, research is required to refine and microminaturize graphics engine technology and to develop appropriate two-dimensional, pseudo three-dimensional, and stereo three-dimensional display formats for Space Station functions such as systems monitoring, construction, rendezvous, docking, and proximity operations. In the field of controls consolidation, research is needed to develop appropriate multifunction interfaces using flat-panel, tactile, touch, and voice I/O technologies. In the field of workstation design, research is needed to expand the design methods and concepts and to provide human factors guidelines for optimum human interface for the monitoring and control of automated and knowledge-based systems.

Voice Recognition and Natural Language Understanding

In addition to extending capabilities of natural language access to data bases, much of the current research in natural language is directed towards determining the ways in which the context of an utterance contributes to its meaning and developing methods for using contextual information when interpreting utterances. For example, consider the following pairs of utterances:

(1) SAM: The locknut should be tight.
JOE: I've done it.

(2) SAM: Has the air filter been removed?
JOE: I've done it.

Although Joe's words are the same in both cases, and both state that some action has been completed, they each refer to different actions - in one case, tightening the locknut; in the other, removing the air filter. The meanings can be determined only by knowing what has been said and what is happening.

Some of the basic research issues being addressed are

* Interpreting extended dialogues and texts (e.g., narratives, written reports) where the meaning depends on the context
* Interpreting indirect or subtle utterances, such as recognizing that "Can you reach the salt?" is a request for the salt
* Developing ways of expressing the more subtle meanings of sentences and texts
* Interpreting language that is "ungrammatical," e.g., slang or dialects (This is particularly of interest for spoken language.)

Many of the research issues of speech and natural language understanding will benefit from DARPA research in these topics. The effort here should consist of adapting research and devices to the space environment.

Computer Vision

Although vision systems are becoming available, there are many remaining research problems. Basic research in computational vision is devoted to understanding how further knowledge and reasoning can be used to interpret images, particularly so-called natural scenes, such as those found outdoors, where there are no restrictions on the

environment, the objects, or the lighting. Major research topics include

* Computational theory of shape recovery

* Model-based vision systems

Research also needs to be done to increase the flexibility of images that can be processed by including such capabilities as

* Identifying objects that overlap

* Accommodating for change in perspective

* Having fewer requirements on lighting conditions

Other research problems currently being explored include

* Representing knowledge about objects, particularly shape and spatial relationships

* Developing methods for reasoning about spatial relationships among objects

* Understanding the interaction between low-level information and high-level knowledge and expectations

* Interpreting stereo images, e.g., for range and motion

Relational Data Bases

An expert system that deals with objects in the world must have a model of the object that provides information required for reasoning about the object. The CAD data base augmented with additional data, such as data that explains the design choices that have been made, would provide this type of information. Research must be done to examine the various classes of expert systems to be used on the Space Station and ground support stations to determine the nature of the data base information required.

Improved user interfaces to access and modify data bases in a simple and natural manner are of great importance. Research in natural language understanding would be pertinent here.

Distributed Processing

The Space Station will be much more complex than any onboard distributed system of the past, and a number of important research and development issues must be addressed long before systems of this complexity are constructed. Among these are

* Develop and evaluate architecture design concepts based on careful study of projected requirements and possible implementations. New ground must be broken in developing integrated design concepts which include all of the types of processing required (from subsystem-embedded computers, to fault-tolerant control and autonomy processors, to special purpose front-end processors and high-speed data processors for support of experimental payloads). Current programs, such as the NASA High Speed Processor, are addressing portions of this problem, but a comprehensive examination of the total computing architecture is needed if systems are to be developed which can be used and evolve as new experiments and technology are introduced over a period of years.

* Define modular implementations which can use the same basic hardware and software components to implement a large portion of the various computing functions provided in the system. A well-defined architecture often uses a small set of powerful primitives to provide needed services while avoiding special cases which apply only to a few operations.

* Develop a small set of intercommunications structures with necessary fault-tolerance characteristics and which supply different communications services for different bandwidth applications. Hopefully, some degree of format compatibility can be obtained between the various structures, and they will be extensible as new devices are added to the network.

* Define the characteristics of virtual subsystems which are created when computers are embedded within.

Functional interfaces can be created which simplify commanding, system integration, testing, and the implementation of autonomy and fault-recovery features.

* Software executive concepts are needed to define both local and global executives for use within the various processors. How processes are assigned to processors, how they are scheduled, how they communicate, and how they share resource objects are some of the results needed here.

* Testbed experimentation is essential to understand onboard systems of the complexity of the Space Station, and it is required before prototype developments can be initiated. A testbed should not be started before a thorough architecture requirements definition is complete. It can then be used to verify and refine architectural concepts, and to develop software of the type that will be eventually used. Software executive concepts can be validated along with developing procedures for data storage and management, and communications strategies can be tested to validate the flow of data and control messages. It is important that the scope of a testbed be clearly defined and limited to proving the computing concepts to be used so that relevant results can be obtained in a timely fashion.

As the Space Station operates over a period of years, new technologies are expected to become available which will provide increases in performance by at least an order of magnitude. Examples are gallium arsenide signal processors, wafer-scale parallel processors, and gigabit bandwidth communication links. To develop a distributed processing architecture which can remain viable as technology changes is a serious challenge. Thus, planning for technology growth must be an important part of the architecture development. Part of the answer lies in hierarchic design. VHSIC technology should provide a level of performance which will remain adequate for many years in the core portions of the system which are dedicated to command, control, and autonomy functions. A modular approach should be taken for computational and communications services supplied for experimental payloads, since these will have computing demands which will grow with the supporting technology. Periodic equipment upgrades can be expected.

It is expected that ground-based processing will make use of high-performance local area networks that employ fault tolerance to achieve high availability and maintain the integrity of large data bases. Although this type of technology is being developed, and a commercial version running a distributed environment will soon become available, there are a number of research areas which should be pursued to improve this type of technology for Space Station applications. These research areas are

* Efficient implementation of atomic transactions to allow graceful recovery when a computer fails during a series of object updates.

* Developing techniques for maintaining data consistency when the network becomes partitioned due to a bus or processor failure. When a failed unit comes back on line, its disks may contain obsolete copies of replicated data.

* Hardware-assist techniques for improving performance. In order to maintain replicated copies of data, a large overhead in network traffic is required to maintain synchronization while providing object locking and atomic transactions. A large part of this overhead can be removed by providing specialized hardware support and specially tailored communications protocols (e.g., ring voting, lock caches, etc.).

* Techniques for providing full fault tolerance in a subset of the computations within the network (to be discussed below).

Fault-Tolerant Processing

For heterogeneous onboard distributed processing of the type expected on the Space Station, there will be a variety of different

fault-tolerant requirements which will require the use of different fault-tolerant techniques for different types of functions for a satisfactory implementation.

To meet these varying requirements in a cost-effective fashion, it is necessary to develop a variety of fault-tolerant processing approaches for different parts of the system in a hierarchical fashion. Core control processes, which may be triplicated with voting, an expensive form of massive redundancy required for comprehensive fault tolerance, may be operated more efficiently in single self-checking processors, relying upon the core control elements to aid in recovery if a fault occurs. High-speed front-end processors used for processing high-rate sensor data will require high availability and should not be bothered by an occasional data error. Here, where processing demands are likely to greatly exceed available resources, it may be necessary to rely on external help from core processors both to detect faults and to effect recovery.

In addition to tolerance of computer faults, a similar hierarchy of autonomy mechanisms must be developed within the distributed system. Software means of detecting anomolies in subsystem operations, and strategies for dealing with system-wide effects of unexpected events, will be necessary.

Fault-tolerant processing and autonomy development will be critical components of all phases of system development through the computer architecture requirements definition, testbed development, and prototype construction. There are still many unanswered questions regarding the best way to implement these functions.

Fault tolerance should be an integral part of the architecture definition of the Space Station. Research into fault-tolerant techniques in heterogeneous multilayered systems is needed. Current reliability modeling techniques are incapable of dealing with systems of this complexity without making very gross assumptions about their structure and behavior. Techniques for verifying the fault-tolerant features of distributed hierarchic systems have yet to be developed. A combination of experimental fault insertion and analytic fault modeling can give insights about the effectiveness of autonomy and fault-tolerant mechanisms, but quantifying these performance levels is still an unsolved problem. Fault metrics need to be developed and appropriate standards applied to various processing, data transfer, and data storage functions.

<u>Tolerance of software and design fault</u>. The standard way in the past to deal with design and software faults has been to perform extensive testing in hope of eliminating them before launch. With systems as complex as the Space Station, it is unlikely that all such faults can be found and eliminated by testing. This is a very difficult and relatively new research area. Research which has been conducted in this area has taken two basic directions. The first, designated recovery blocks, uses modular software and performs acceptance tests on results as programs transition from one module to another. Alternate software modules are executed if anomalous behavior is detected. The second approach, designated N-version programming, operates multiple independently written copies of software and votes them at designated checkpoints to mask faults. When multiversion software is operated on different types of hardware, it may be possible also to circumvent both hardware and software design faults. Both of these approaches are expensive and will probably be reserved to highly critical applications.

Computer Technology

The current VHSIC program and other VLSI developments in industry are providing a technology base which can be exploited in the Space Station. These programs, which are heavily oriented to producing complex and fast devices, have centered on producing devices for specific applications. For example, the VHSIC chip sets are oriented toward specific military applications. Important research is needed on architectural issues of how the technology can be used for a broader class of problems in government and industry. It remains quite expensive to develop a custom circuit, so architectures are needed that use a

small number of chip types which can be used for a wide range of applications. It is important to design the Space Station computing complex in such a way that a dozen or fewer custom chip types can be used as building blocks to interconnect the various processors and memories into a distributed system.

Multilevel architectures have been identified which are amenable to these highly modular implementations using a small set of custom "glue" chips. Standard chip types have been identified which allow construction of high-speed self-checking processors, with standard intercommunications interfaces. Other chips allow these single processors to be combined into very high-speed multiprocessors and additional port chips allow these multiprocessors to be connected into arrays of high performance multiprocessors. Building-block approaches of this type are needed to efficiently utilize VHSIC technology in the Space Station.

Because of the high degree of complexity of VHSIC chips, highly automated computer tools are needed to design them. This is an active area of research both in the government and in industry. The VHSIC program has stimulated development of design automation systems and has specified testability requirements for the chips produced. Many recent design systems allow different simulations to be carried out at various steps of the design process to detect errors before a chip is fabricated, but many errors can still slip through the design process. After a complex chip is fabricated, it is extremely difficult to test, because there are only a few connection pins to access thousands of logic circuits inside. Logic design techniques have been developed to improve testability of chips (such as IBM's Level Sensitive Scan Design and the inclusion of test circuits on-chip). The problem of chip testability is only partially solved, however, and this is another area in which research is badly needed.

As chips become more complex, their logic devices become much smaller, have lower operating margins, and operate at higher speeds. It is expected that transient errors will occur much more often, and internal fault-detection circuitry will need to be employed to detect and correct these faults before information damage occurs. It is also possible to include redundant circuits on a chip to effect recovery if a failure occurs inside or to increase production yields by circumventing non-functional logic when a device is produced. Both of these are active areas of research and need to continue. Products of this research can greatly improve reliability and performance in the Space Station.

Finally, it will be necessary to identify special-purpose devices needed within the Space Station (e.g., large bubble memories, signal processing logic, fiber optic communication port interfaces, optical storage devices) and to initiate the appropriate VLSI developments.

Software

There is considerable effort currently underway within DOD to address software issues, particularly in the STARS (Software Technology for Adaptable, Reliable Systems) program and the Software Engineering Institute at Carnegie-Mellon University. These activities are seeking improved methods for software production and maintenance for reliability and cost savings. NASA can benefit from these activities. An application from a space station autonomous system development could provide an excellent basis for applied research and testing of the software technology being developed under STARS.

Research in reliable software development and measurement techniques is needed, since autonomous systems require very high reliability in their control software. This work should include reliability assessment and software quality metrics. Methods for fault-tolerant software also need research to address both software able to operate within a faulty system as well as software built to tolerate design and implementation faults written into the software by mistake. Fault-tolerant software is complementary to hardware and system fault tolerance, and all these areas need research.

Programming language research should focus on automatic programming systems that help eliminate the potential for human error in developing new software. Automatic programming systems are still in the conceptual stage, and much research is needed before such systems can be used in production. The benefits of automatic programming systems will effect the initial development of more reliable software for the Space Station as well as the modifications to subsystems that will be required for the evolutionary growth station and the maintenance and enhancement of software existing on the Space Station. It is expected that NASA neither wants nor can afford to have programmers in space; hence, very high-level programming languages, application generators, and automatic programming systems will be necessary for the onboard or visiting crew.

Information Networks

Initial investigations have established three requirements for a space station information network: high performance, reliability/fault tolerance and extensibility/modularity. Massive communication capacity will be needed to support transmission of satellite images and multiple, real-time video channels. The communication workload will be heterogeneous, including voice, video, and data. The workload composition will not be static; not only will there be transient demands, but long-term demands will also evolve with the Space Station. Simply put, the Space Station needs high-capacity networks capable of adapting to changing, heterogeneous communication workloads. The integrity of the Space Station and the lives of its personnel will depend on continuous and reliable distribution of data for monitoring and control of the Station. As the Space Station changes and expands, the information system must evolve gracefully. A number of important technological areas must be addressed:

* A network mesh has multiple data communication links between network user sites or nodes, and has the physical appearance of a woven braid. This form of topology helps meet the requirements with the following features: (1) simultaneous adaptable data communication links offer dynamic and high-performance accommodation, and (2) alternate communication links provide a capability for fault-tolerant properties. This effort should be to research and characterize the architectural issues of the mesh form of network, including determining the appropriate type and form of protocols.

* Fiber optics with wavelengths division multiplexing (WDM) offers a reasonable means of achieving both high performance, by its inherent high bandwidth capacity, and extensibility, by utilizing a multiplicity of wavelengths available from semiconductor lasers. An example of the expandable capacity can be seen from a single wavelength system which is operating at 50 megabits. By adding four different wavelengths in the same common fiber, plus an optical multiplexer/demultiplexer, the system data rate can be increased to 200 megabits. This will provide an easy technique for providing additional data capacity to existing fibers. A greater data capacity is available by adding additional wavelengths to continue to expand the data handling capability of an information network. This effort should be to research and develop fiber optic WDM components and devices and WDM fiber optic networks.

* A network node forms the user interface into the network, controls user access to the network, provides adaptable multiple path data communications to/from other nodes, and provides for overall control of the network. With presently available technology, the use of optical fibers requires the use of optical to electrical (O/E) and E/O conversion at each node. Since these conversions require additional components and additional power and represent a potential system bottleneck, it seems there would be much to gain by constructing nodes which minimally would allow the passage of optical signals without O/E and E/O conversion and which should, ideally, perform many of the adaptable logic functions using optical rather than electronic techniques. The present state

of optical technology suggests that a first generation optical node will be a hybrid opto-electronic device in which the switching will be optical but the logic and control signals will be electronic. Future generations of the node could be heavily optical as optical computation and logic capabilities improve.

* Video service will be required in the Space Station information systems to extend vision, to communicate data, to provide recreation, entertainment, and leisure for the crew and customers, and to record and store scenes and data, as well as for private communications, for inspection purposes, and for training simulation visual displays, graphical displays, computer terminal and other workstation displays, and caution and warning displays. In recent years there has been an explosion of technologies and methods applicable to <u>digital</u> video. It will be possible in the future to employ digital video from the source (digital video cameras), through the distribution network, and to the display (digital video monitors). The objective of this effort would be to identify and research an integrated and compatible set of equipment, procedures, and networking for a digital video system to service Space Station requirements.

* Networking Operating Systems: The state of the art in decentralized computers is succinctly stated by Jensen and Pleszkoch (1984).

  "Almost all work on 'distributed' systems in general and 'distribution'/ network operating systems in particular have been evolutionary to an extreme - most of the resource management concepts have been simple adaptives of centralized ones burdened by inappropriate and even counterproductive artifacts. The ineffectiveness of constructing airplanes which fly by flapping their wings was recognized early; but corresponding realizations about distributed systems have largely not yet taken place...."

  The need here, in order to support Teleoperator/Robotics for a manned Space Station, is the development of an advanced network O/S to provide decentralized management of resources, with functional singularity of purpose where needed, while acting with imperfect data and surviving failure through replication and recovery of information, and improving performance with concurrency.

INFRASTRUCTURE TO SUPPORT THE TECHNOLOGY BASE

In order to effectively support and coordinate the activities of the large number of people and organizations, the program should focus attention early on adequate infrastructure for the enterprise.

There should be three phases of activities. At the beginning of the program major emphasis should be placed on the consolidation of state-of-the-art technology to enable rapid capitalization and maximum resource sharing. A second phase should be designed to take advantage of early products of the program to enhance overall capabilities. A final phase should bring about a transition of the activities in the infrastructure to make them self-supporting. Any high initial investment in equipment, services, and training would be greatly rewarded with a most critical resource - trained personnel.

The infrastructure is categorized by specific activities to be performed. The most immediate need is availability of the products of technology so as to bootstrap the development process. Where appropriate, common processing equipment should be provided to selected participants in the first years and supplemented with more advanced equipment as it is developed in the program. Common access to high-performance networks should be provided to facilitate communication between sites and shared use of computing resources.

Next, a set of activities should address common access to services and tools that are the means of designing and building the elements of the new technology. These include rapid-prototyping implementation services providing foundry access to VLSI/VHSIC and GaAs fabrication lines as well

as access to higher-level system implementation services. Computers are to be used extensively in the design and analysis of new systems, and these hardware and software tools should be shared between sites by exploiting the common hardware configurations, programming languages, and network communication facilities.

Additionally, specific activities should encourage collaboration between researchers through the development of interoperability standards. Strong interaction with the university community should be coupled with the use of the technology in the form of embedded instruction to accelerate the training and development of personnel.

The result would be a powerful expansion of the traditional concept of infrastructure. The program would produce not only an advanced technology base in the form of facilities, equipment, institutions, and knowledge, but also the methods for using it and accelerating its growth.

Capital Equipment

Hardware and software tools that could be common to a large number of research efforts should be developed early in the program to enable widespread use of advanced teleoperator and robot prototypes, symbolic computers, and communication systems in both laboratory and embedded applications.

No element of the infrastructure is as important as the need for widening the network connection among the various participants of the program. Beyond the obvious advantages of sharing resources and facilities, the network would be a means of promoting synergy between researchers located at different sites. This network should include other agencies (such as DOE, DOD, and NSF) in developing a common plan for leased wideband communication facilities to be made available by the common carriers. Existing networks, such as ARPANET, should be examined for suitability to satisfy this requirement.

Services

The physical construction of complex equipment is a difficult and time-consuming task, even when all the essential design details are understood. A set of services should be put in place that simplify this process, reduce cost, and provide rapid turnaround.

A service should be established to allow the rapid implementation of full-scale systems with the goal of enabling the assembly of complete prototype models from initial designs within a short period of time. Sources could be solicited for the design and manufacturing of "system kits" intended to facilitate interoperability and experimentation in new equipment designs. These standardized hardware and software environments would provide the physical means of easily integrating and assembling systems into predesigned modules using design frames for embedding unique custom designs as part of these systems.

Computer Tools for an Integrated System Development Environment

An advanced system development environment should be constructed as a framework for consolidation and integration of the design and performance analysis tools that are produced by this program. This environment would set the standards for tool development and facilitate the sharing of the products of this research between sites.

The new generation of hardware should be developed using new high-level tools that are built upon state-of-the-art research in VHSIC and VLSI design. These tools should be extended upward to enable system-level design, assembly, and test in a rapid system prototyping environment. It is here that the use of computing technology as a tool to create new computing technology is most obvious. In the functional design of a new machine architecture, its performance can be evaluated through emulation. It is expected that dedicated hardware emulation machines would be used to assess a number of

architectures for which construction will be difficult or costly. Likewise, advanced hardware and software approaches to physical design aids would enable more rapid and robust system design.

An integrated rapid software and systems prototyping capability would be needed to support the development and application of multiprocessor systems. This capability should be developed by building upon advanced software and systems development environments such as Ada and common LISP and extending them to support multiprocessor targets. The major problems that need to be solved are to apply these architectures effectively and achieve the required performance and resource allocation for processor, memory, communication, and mass storage. In addition, the application system developers need support for using the new architectures in terms of the virtual machine interfaces that will be developed to manage resource allocation. The software and systems activities would produce the most generic software to support the application specific software. This includes programming languages, system software, and design and performance analysis tools for multiprocessor targets. As the technology matures, resource allocation will become more automatic and higher-level design environments for multiprocessor architectures should be developed.

Standards

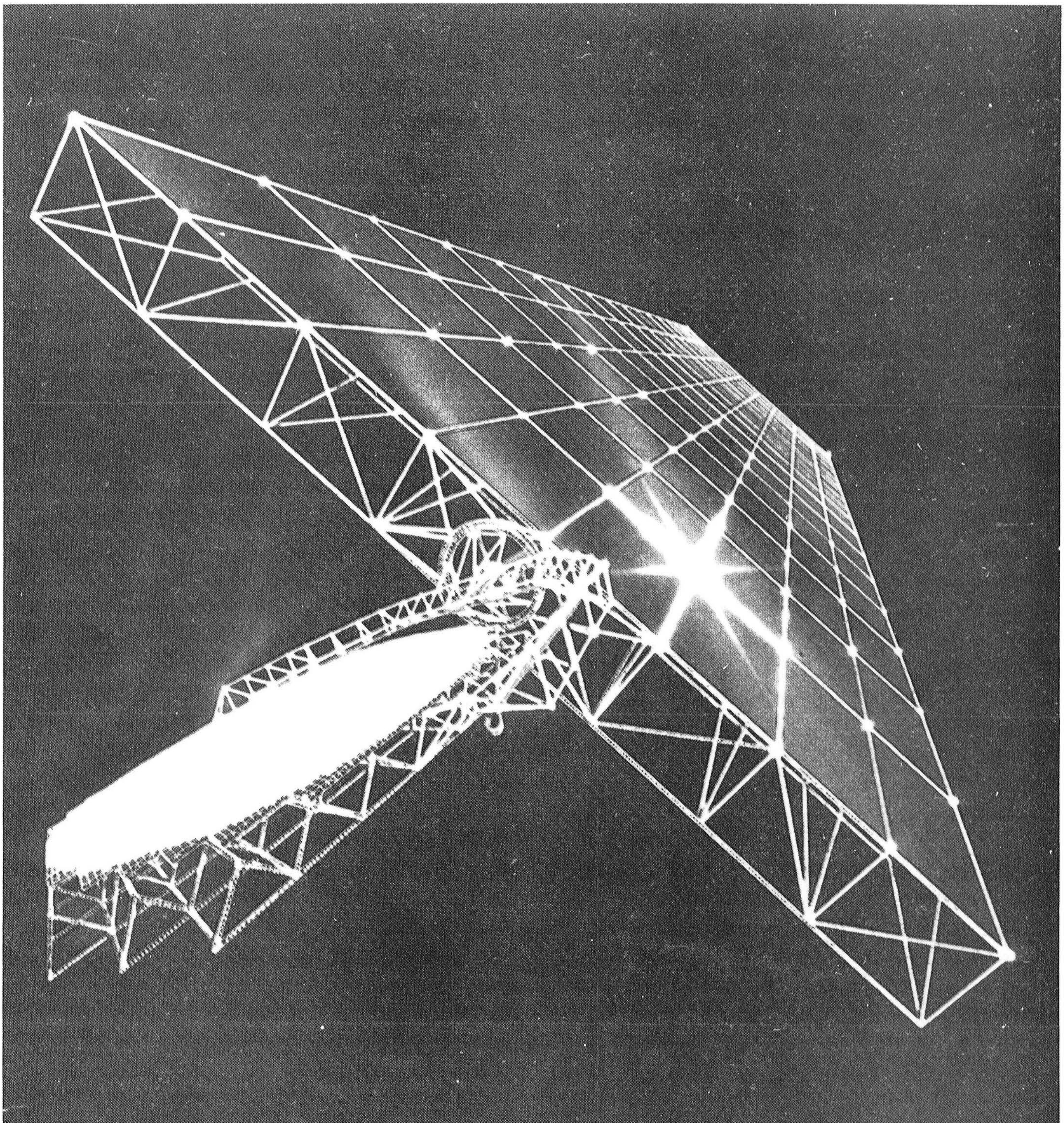
To integrate hardware and software to perform basic system functions, and then to integrate those functions into systems, will require interoperability research. A key ingredient will be the set of protocols that allow interaction between modules. It should be possible, for example, to access information in a knowledge base from a speech understanding system or to make available vision or natural language to a navigation system. Outputs from any of these should be available to AI-based simulation and display systems.

One should envision developing system interoperability protocols to the point where couplings of hardware, software, and peripheral devices may be selected and configured readily. This would include capabilities for teleoperation, robotics, speech input, vision, graphics, and a host of intelligent system tools including domain-independent expert system developmental tools and a LISP machine.

SELECTION OF TECHNOLOGY FOR RESEARCH AND DEVELOPMENT

Undoubtedly there will be a number of possible alternatives to choose from that could satisfy possible automation designs. The risk of being able to implement these alternatives along a prescribed schedule must be measured relative to the goals for the Space Station. Such an assessment should reveal the research and various development programs that would support the design. Specifically what technology do you push and when do you push it? The rationale for the technology selection should be clearly defined at the outset of the planning activities. The responsibility for developing the rationale should lie within the Space Station Program Office.

The goals for the Space Station are related both to maintaining a permanent presence in space and to enhancing our knowledge about building robotic and computer systems. The design philosophy should not only address the immediate and growth needs of the Space Station but it should also address the benefits to the U.S. economy in terrestrial applications. Wherever possible, automation areas should be identified that benefit both the Space Station and terrestrial application needs. This may mean, for example, that functions common to a large number of applications be clearly defined and assessed both in terms of prospects of successfully developing new technologies in a timely way. By clearly identifying these generic elements, it should be possible to define a technology development program that supports both the Space Station and terrestrial applications.



Chapter 7

TRANSFER OF TECHNOLOGY TO TERRESTRIAL APPLICATIONS

IMPORTANCE OF TECHNOLOGY TRANSFER

Congressional Directives

The Space Act of 1958 (PL85-568) requires that NASA transfer the results of its mission-related research and development to nonspace private and public sectors of U.S. society. In 1979 the Space Act was amended to direct NASA to assist in bioengineering research, development, and demonstration programs designed to alleviate and minimize the effects of disability. The Stevenson-Wydler Technology Innovation Act of 1980 (PL96-480) encouraged the exchange of scientific and technical personnel among universities, industry, and government. Its purpose was to stimulate improved utilization of federally funded technology by industry and by state and local governments.

In report 98-867 of the Committee of Conference to accompany bill HR 5713, which authorizes funding for the Space Station, it states, "*The conferees both intend and expect that the technologies of Space Station automation and robotics will be identified and developed not only to increase the efficiency of the station itself but also to enhance the nation's technical and scientific base leading to more productive industries here on Earth.*"

NASA thus has both an historical mandate for technology transfer and specific direction to see that automation and robotics technology developed for the Space Station be used to increase the productivity of U.S. industry.

Economic Rationale

Present economic indications point to the need for major changes in U.S. industry. These changes include an increase in technological innovation. The U.S. real GNP growth rate dropped from 4.2 percent, for the period 1960 to 1973, to 2.4 percent for the years 1974 through 1981. According to the present administration, this recent rate of economic growth is not sufficient to meet the nation's needs.

From 1960 to 1980, Japan and West Germany captured 30 percent of the U.S. market share of total world trade in manufactured goods. The U.S. balance of trade with Japan is particularly poor in specific high-technology industries.

The trend in productivity growth is not good. Since 1960, U.S. productivity has increased only 2 percent per year. In Japan, the annual rate of increase was 9 percent and in West Germany 3 percent.

Productivity is an important measure of economic capability because it reflects the ability of domestic producers to transform human and material resources into commercial goods and services.

Productivity is related to technology in that if the machine, information, and organization technologies are powerful and efficient, then the labor force will be more productive. According to Dr. George A. Keyworth, President Reagan's Science Advisor and Director, Office of Science and Technology Policy, "the real underlying problems we are facing" include "productivity, innovation, and the general health of our science and technology base." Further indication of a link between productivity and technology comes from the fact that R&D spending, as a proportion of GNP, has declined in association with the decline in productivity.

In light of the current economic situation, technology transfer is seen as a key ingredient in the effort to improve the vitality of the U.S. economy. With decreases in the rate of R&D spending, technology transfer takes on

increased significance as a means of improving the technology component in U.S. industry. The purpose of technology transfer is to provide the general economy the advantages of a broader technological base without duplicating the R&D already done.

For any program of technology transfer to be successful, it must be economically viable. That is, the incremental benefit to society must be at least equal to the incremental cost to society. New technology transferred to industry can reduce production costs, improve product quality, or generate new products altogether. Productivity is increased, and industries become more competitive in world markets.

Some studies have attempted to quantify the economic benefits of technology transfer. Studies by Mathtech (1977) and Denver Research Institute (1979) applied a benefit/cost analysis to selected NASA technology transfer programs. The Mathtech report on nine projects shows an average benefit/cost ratio of 22. The Denver Research Institute report used a broader definition of costs and "lower bound" benefit estimates to arrive at an average benefit/cost ratio of 4. Even the more conservative report indicates that technology transfer, when done right, can have significant economic payoffs.

FACILITATION OF TECHNOLOGY TRANSFER

This section describes a plan for the transfer of NASA-developed automation and robotics technology to U.S. industry. The objective of this transfer effort is to increase productivity and competitiveness of U.S. industry in world markets. It should be emphasized that the plan does not describe new policies, but rather suggests how existing NASA policies and mechanisms can be used to transfer advanced automation and robotics technology.

In an effort to develop a technology transfer plan that would be both effective and efficient, two guidelines were established:

* One objective of the plan should be to establish a mechanism for consideration of industry's needs during the definition and preliminary design phases of the Space Station. At this stage, certain critical decisions will have a significant impact on the transferability of the technology to U.S. industry. For example, Space Station use of existing and evolving industry standards for data communication in automation could reduce the time and funds required for adaptation of the technology to an industrial environment.

* The plan should utilize NASA's established technology transfer mechanisms whenever possible. This approach would not only minimize the funds required for implementation of an automation and robotics technology transfer plan, but would avoid confusing industry by the existence of more than one NASA network with the objective of transferring aerospace technology to U.S. industry.

Considerations of Industry's Requirements

This section of the report discusses why one should consider the needs of industry during initial definition and design of the Space Station. Since Congress intends that automation and robotics be used not only to increase the efficiency of the Space Station, but also to lead to more productive industries on Earth, NASA needs to look beyond the Space Station when including automation and robotics in Space Station definition and design.

Congress has recognized the opportunity that the Space Station program offers to stimulate the advance of a range of automation and robotics technologies. <u>Examples of such technologies</u> include advanced vision sensors, control algorithms for robots with multiple types of sensors and manipulator systems with advanced multiple degrees of freedom. In the area of imbedded real-time computer control software, the Space Station program can lead to prototypes of the control software necessary to run the automation and robotic systems of the automated factories of the future. Examples of automatic factory software requiring significant development are real-time manufacturing resource control software, dynamic job shop scheduling software, and

integrated computer-aided design, engineering, test, and manufacturing software. In some cases, these advances in both automation hardware and software will be direct enhancements of existing automated space vehicle technology such as sensor pointing systems, remote manipulators, and operation scheduling software.

Data communications and control. Part of defining the context in which this technology transfer will take place is establishing the state of automation and robotics technology in American industry today. At present, automation in American industry is characterized by a small number of very large corporations having various degrees of large, highly integrated, automated design and manufacturing systems. Medium sized companies exhibit smaller degrees of automation and are characterized by islands of automation in the sense of stand-alone automated machine tools and computer-based bookkeeping procedures. The penetration of automation and robotics into small manufacturers is very small indeed and is largely limited to microcomputer-based business management systems.

The current state of automation and robotics in American industry is characterized by the increasingly central role being played by the flexible manufacturing system (FMS) and the flexible manufacturing cell (FMC). Several years ago, much of the trade literature was full of the buzz phrase "automatic factory." The actual engineering integration and implementation of the totally automatic factory has proved to be extremely difficult and expensive. In a tactical retreat to less costly integrated automation, the FMS concept has evolved in American industry to address a somewhat smaller objective - that of a completely flexible production system for a finite family of products. By constraining the size, geometry, and materials of the products to be produced, the engineering problem is reduced to one of designing a manufacturing system that has to perform only a limited combination of operations on the raw materials to produce the desired end product. While flexible manufacturing systems are designed to produce an optimal, finite range of products, flexible manufacturing cells constrain themselves to smaller production requirements still. A good analogy to the concept of a flexible manufacturing cell would be the microgravity continuous flow electrophoresis system currently being tested by McDonnell Douglas onboard the Space Shuttle for production of a range of biological products. A single automated electrophoresis unit has the flexibility to separate a large number of different biological feed stocks into viable products, including blood cells, cell components, antigens, hormones, and proteins. In the same vein, the Space Station can be considered not so much as an automatic factory but as a flexible manufacturing system made up of many flexible manufacturing modules or cells. Typical examples of these cells would be the continuous flow electrophoresis production module; electronic materials (crystal) growing modules; metals, glasses, and ceramic fabrication modules; fluid and chemical production modules; and microsphere production modules. Just as in modern American manufacturing job shops, Space Station operations must schedule the jobs of each cell due to limited amounts of such resources as power, feedstock, and data communications. In short, the practical operating time and resource constraints of the flexible manufacturing system that is the Space Station are the same generic operating constraints that limit the productivity of the thousands of medium and small American companies every day. Providing commonly available, automated solutions to these generic real-time operating problems would have a profound impact on the productivity of American companies of all sizes. The automation and robotics technologies which have the greatest potential for solving these real-time operating problems and enhancing American productivity may not relate to hardware but rather to control algorithms and control models used to improve the productivity of operations.

Collaboration with American industry on Space Station technology spinoffs would be facilitated if NASA were to adopt the automation standards of industry where possible. These standards, specifically those related to automation, arise from a number of organizations including the Institute of Electrical and Electronics Engineers (IEEE),

the Electronics Industries Association (EIA), the American National Standards Institute (ANSI), and others. For example, a major, current thrust by industry is in the area of automation data communications on the factory floor. American industry has a critical need for local area networks (LAN's) that allow a whole range of computers and computer-controlled equipment to intercommunicate on the factory floor. Similarly, a key element of the Space Station as a flexible manufacturing system may be an onboard local area network. Factory LAN's have architectures which are based on newly adopted standards. Two examples of these standards are the international standards organization Open Systems Interconnect (OSI) reference model for data communications and General Motors manufacturing automation protocol (MAP) reference model.

The international standards organization OSI model is rapidly becoming the worldwide standard for digital communications. As a result, companies are rushing to develop both hardware and software implementations under various levels of the OSI protocol. There is an emphasis on implementation of the OSI model in local area networks using the various IEEE-802 protocols, including the token-passing bus protocol and the token-passing ring protocol (figure 22).

As illustrated in figure 22, the IEEE-802 protocols relate to the bottom two layers of the model. Because of the nature of the layered model, the adoption of a particular standard at the physical and link levels does not restrict one's choices for the higher levels. Within each layer, functions exchange data according to the established protocols for that layer. Each layer draws upon a well-defined set of services provided by the layer below and provides a similarly well-defined set of services to the layer above. As long as these service interfaces are preserved, the internal operations within a layer are unconstrained; therefore, an entire layer may be removed and replaced if so dictated by changing user or technological requirements. This characteristic of the layered approach makes it a powerful tool in designing adaptable, evolutionary systems.

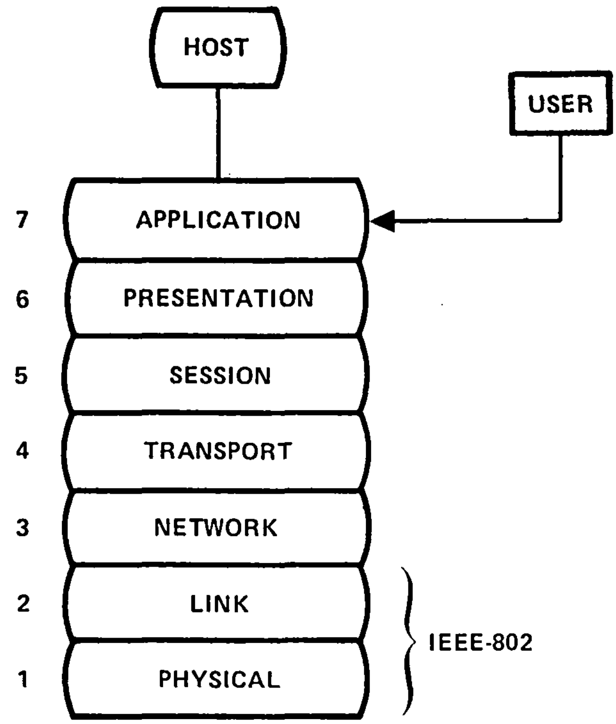


Figure 22.- Layered OSI model for data communications.

General Motors has adopted the IEEE-802 token-passing protocols for its MAP specification. According to General Motors' Ron Floyd, GM now has installed some 20,000 programmable controllers and 2,000 robots. If other computer-based control product devices are included, the number of intelligent devices installed in GM's manufacturing areas totals more than 40,000, with a projected 400- to 500-percent increase in the next 5 years. A severe problem exists for GM at present in that few of these 40,000 devices can talk to each other. To solve its problem, the company is attempting to convince control manufacturers to adopt the IEEE-802 data communications standards so that one form of computer-controlled equipment can talk to another, regardless of the original manufacturer.

There are those, however, who caution that LAN's may not be the best approach to automating a factory which has a very large number of devices (Taylor, 1984). They argue that network theory is based upon a telephone system model of communications, while

factories operate according to a bulletin board system. That is, instead of flowing along a large number of two-way paths, factory information is posted so that all interested parties can read it from a common source. An alternative to the LAN approach has been proposed based upon a very fast fiber optic bus which turns the entire factory into a single address space. The appropriateness of such a model for the Space Station has yet to be fully explored.

The need to adopt standardized approaches in Space Station automation and robotics goes beyond data communications. Standards would also be considered for embedded control systems architectures for the robotics systems and devices that are proposed for the Space Station. An example of a consistent, logical control architecture for robotics systems is the National Bureau of Standards (NBS) model for hierarchical automatic factory control. The DOD is researching other embedded control system architectures.

The implementation of the NBS model will soon reach a point where it can be used as a prototype to a second generation system for automated flexible manufacturing system control as required for Space Station automation. American industry, on its own, is moving to adopt internally supported standards for the various generic functions of the automatic factory or flexible manufacturing systems. In order to satisfy Congress' wishes in the transfer of Space Station automation and robotic technologies, it behooves NASA to adopt, for the Space Station system and subsystem design and architecture, as many industry standards as will adequately meet the functional and performance requirements of the Space Station program. This will not only minimize costs by maximizing the use of off-the-shelf technology on the Space Station, but should expand the potential vendor pool for Space Station program subcontracts to a large new population of American industrial automation and control vendors, including developers of the latest state-of-the-art and real-time control products. It is possible that many of the standards which American industry has or will soon adopt will meet the vast majority of the Space Station's functional and performance requirements. To facilitate the transfer of automation and robotics technology, current and imminently pending industry automation standards will be considered for appropriate Space Station applications.

Software. Another aspect of the Space Station design which will have a beneficial impact upon the technology transfer effort is software standardization. A standard language for the Space Station helps avoid costly program revisions when the computing environment changes and makes it easier for someone who did not write the software to maintain it later on. In addition, if standards chosen for the Space Station are the same as those commonly used in industry, then software developed for the Space Station will tend to be compatible with computing environments elsewhere. If software on the Space Station will run on existing computer systems in industry, the chances of successful transfer are greatly enhanced. While much software will be specific to Space Station systems, there will be a considerable amount which has general applicability or could be modified to fit another application. Decision making systems for monitoring and control or software for robotic control are examples of Space Station software which could easily prove useful on Earth.

In common with all other user organizations, the Department of Defense has faced this same situation in terms of their so-called "embedded computers" in weapons systems. Because of the magnitude of their activities, they have developed their own standard language for their applications. The language, known as Ada, was developed by the Higher Order Language Working Group of DOD with help from a very large number of individuals and organizations throughout the world, such as industrial groups, technical organizations, and universities (Booch, 1983).

Adherence to the Ada standard is being promoted by the DOD-sponsored development of a compiler evaluation laboratory. The laboratory is establishing a validation suite of several thousand test programs which test not only that all the features of the language are implemented, but also that extensions have not been added. Before a vendor can state

that it has an Ada compiler, the compiler and run-time system will have to successfully compile and execute the validation suite of programs.

In addition to the effort to build Ada compilers, there is a companion effort to produce a software development environment for Ada. The development system, called the Ada Programming System Environment, will include such things as syntax-driven editors, intelligent linkers and loaders, debugging aids, and other development tools.

The momentum behind Ada is considerable. DOD has dictated that Ada will be used for all its embedded real-time system applications, and a $20-million-per-year software research institute is planned to deal largely with Ada issues. By the time of IOC, the use of Ada should be widespread, not only within DOD, but throughout the rest of the world as well. Ada compilers will be available for all major processors, and a large effort will have been made to optimize its execution. For these reasons, Ada will be considered for systems implementation on the Space Station.

Some caution must be exercised, however, by keeping in mind what Ada was designed to do and what it was not designed to do. The designers of Ada desired to create an environment which would encourage good programming practices. By imposing a rather strict programming style, Ada offers considerable advantages for systems programmers in software teams developing and maintaining complex software. Some of the characteristics which make Ada effective in the realm for which it was designed, however, make it less suitable for other uses, such as a general research language for artificial intelligence. In a research environment, the programmer often does not initially have a clear understanding of how best to attack a problem. A language is needed which allows maximum expressive power and flexibility to handle the considerable redevelopment which occurs. Because it was designed to enforce a strict programming discipline rather than to provide maximum flexibility, Ada may be more appropriate as a target language for artificial intelligence programs rather than as a development language.

For artificial intelligence applications, people have traditionally chosen to use special languages designed for the handling of symbols, lists, and relations among objects. The two commonly used languages for these purposes are LISP and PROLOG. Since most existing AI software is written in one of these two languages, and since they are likely to remain the languages of choice for AI applications in the future, it seems advisable to adopt one of them for the Space Station. Of the two, LISP is far more prevalent in this country, while PROLOG has received acceptance in Europe and Japan. There is currently an effort to devise a standard version of LISP, called COMMON LISP, which will run on most of the present LISP machines. The choice of a language for AI applications on the Space Station should take into account the portability of the language for transfer to computing environments on Earth.

There is an additional need for languages which are easy for engineers or systems operators to use in developing and modifying operational programs for digital control. Such languages are called Problem Oriented Languages (POL's). They are usually written to include terms unique to the particular application involved. Thus, a POL for robot control would use such terms as grasp, pick up, release, etc.

These languages can proliferate greatly since they are usually so specialized. Standardization and transportability are preserved by translating the POL statements by means of a string processing language into the standard systems language, for example, Ada. A string processing language which could be used for this task is STAGE-2 or its commercial equivalent TILT. The string processing language matches statements of the POL to the corresponding subroutines or skeletons of the standard systems language as taken from a skeleton library and translates the statements into statements in the standard systems language.

Established NASA Technology Utilization Mechanisms

In 1962 NASA initiated a Technology Utilization Program to meet the technology transfer mandate of the 1958 Space Act. The program has evolved a nationwide network to accelerate and broaden the transfer of aerospace technology to other sectors of the economy. The program is administered by the Technology Utilization and Industry Affairs Division of the Office of Commercial Programs at NASA Headquarters. Technology Utilization Officers at each NASA Field Center coordinate the transfer activities involving that center's technology. Utilization of this established program for the transfer of Space Station automation and robotics technology will provide an immediate, cost-effective access to a network already transferring aerospace technology to U.S. industry. Components of the Technology Utilization program range from technical information systems to adaptive engineering programs. These activities and mechanisms by which they could be used to transfer Space Station automation and robotics technology are described below.

Publications are an important part of the program to inform potential users of the NASA technology available for transfer. *Tech Briefs* is published twice a year and provides information in each issue on more than 200 new concepts, devices, or processes developed by NASA. These technologies are grouped into chapters entitled Materials, Life Sciences, Machinery, Mechanics, Physical Sciences, Electronic Systems, Electronic Components and Circuits, and Fabrication Technology. Interested firms can obtain additional information on a specific topic by ordering a Technical Support Package. Industry utilization of this publication is illustrated by the 160,000 requests in 1981 for additional information on innovations described in *Tech Briefs*. Another publication useful to industry is the semiannual *NASA Patent Abstracts Bibliography*, which lists more than 3,500 NASA-patented inventions available for licensing. *Spinoff* is an annual publication which summarizes the status of NASA's mainline programs developing technologies of the future and describes a representative selection of spinoff products and processes derived from NASA technology. The addition of a chapter in *Tech Briefs* and *Spinoff* devoted to automation and robotics would be an effective mechanism for informing industry of NASA's new technology in these areas. To ensure distribution of these publications to the appropriate industries, the person at each field center designated to coordinate automation and robotics transfer operations would work with the publishing organizations to develop a mailing list.

Applications Centers were established by NASA to provide information retrieval services and technical assistance to clients in the public and private sectors. The network consists of seven Industrial Applications Centers (IAC's) and two State Technology Application Centers (STAC's). Through these centers, clients have access to more than 10 million documents, 2 million of which are in computer-accessible NASA data banks. The scientists, engineers, and computer retrieval specialists on the Application Center staff can identify relevant literature for the client and provide assistance in applying the information to the company's best advantage while charging only a nominal fee for the services. State Technology Applications Centers provide a similar service for state and local governments. Effective utilization of the aerospace technology data base can reduce industry's R&D costs and expedite innovation. The technical reports generated by the program to meet Space Station robotics and automation requirements would be included in the NASA literature bases accessed by the Application Centers.

A Computer Software Management and Information Center (COSMIC) is operated by NASA to assist industry and Government agencies in the utilization of computer programs developed by NASA. Many of these programs are directly applicable to secondary use with little or no modification, while others can be adapted for special purposes at a fraction of the cost of developing an entire program. For example, Magnavox reported a savings of 6 person-months in the development of a digital optical recorder. COSMIC, located at the University of Georgia, has a library of 1,500 programs which perform such

tasks as structural analysis, design of fluid systems, electronic circuit design, and determination of building energy requirements. COSMIC publishes an annual index of available programs and assists customers in identifying programs that meet their needs. Total sales for 1981 were $750,000, and the trend has been one of rapid growth. Software developed in the Space Station automation and robotics program could be made available to industry through COSMIC.

The Corporate Associates Program was initiated in 1980 by NASA in conjunction with the American Institute of Aeronautics and Astronautics. The program involves a series of seminars that are held at NASA Field Centers and attended by executives and managers from many of the nation's largest nonaerospace companies. The seminars bring together high-level industry representatives with NASA scientists and engineers to discuss possible applications of aerospace technology in industry. Workshops could be a valuable mechanism for the active exchange of information between industry and NASA regarding their respective requirements and technologies in automation and robotics.

Applications Engineering Projects involve the collaboration of NASA, industry, and other government agencies for adapting aerospace technology to meet technical needs in manufacturing as well as medicine and rehabilitation. To meet the Congressional mandate of "widest practicable and appropriate dissemination," the goal of the applications engineering projects is for industry to participate in the project and market the successful solution. In this way, the solution is made available to all potential users. An example of a NASA applications engineering project that solved an important problem in manufacturing was the Ultrasonic Bolt Tension Monitor. When bolts are subjected to severe stresses and strains in pressure vessels, bridges, or power plants, over- or under-tightened bolts can fail, resulting in serious accidents and costly equipment damage. NASA technology in the nondestructive evaluation of materials resulted in the development of a bolt tension monitor appropriate for use in industry. The importance of this applications engineering project was recognized by the trade journal *Industrial Research and Development* in awarding an IR-100 award in 1981 for the development of this instrument.

The Technology Applications Team serves as an active transfer agent for NASA's technology transfer program. A major premise of this program is the active participation of industry, Federal and State agencies, and the user community. A technology transfer methodology based upon an active transfer agent serving as a personal interface has evolved from the realization that the passive dissemination of information on technology in itself seldom results in effective technology transfer. This point is illustrated by a quote from the U. S. Congress, 1976:

"The mere availability of information does not cause its transfer or use. Printed materials alone, even expertly prepared, cannot stimulate interpersonal relations, define a problem, answer related questions, involve consulting authorities, provide follow-through on problems or relate to other agencies."

The role of the Technology Applications Team is to identify priority needs and aerospace technology that can meet those needs, then broker the participation of other Federal agencies and industry to develop this need/technology match to the point of commercial introduction. The methodology used by the Applications Team for active technology transfer involves three phases described below and outlined in a Work Breakdown Structure, table 6, prepared by the Technology Applications Team at Research Triangle Institute.

Identify commercialization opportunities. This phase involves the identification of significant technology requirements of industry and NASA technology that could be utilized to meet those requirements. The Applications Team works closely with individual manufacturers and industry associations to identify technology requirements. For example, the Applications Team has contacted over 50 trade associations

TABLE 6.- WORK BREAKDOWN STRUCTURE

Level 1	Level 2		Level 3		Level 4	
Technology Transfer Program	A.0	Identify Commercialization Opportunities	A.1	Identify Technology Requirements	A.1.1	Conduct and Document Advisory Panel Meetings
					A.1.2	Interviews with Industry and Government Experts
					A.1.3	Literature Reviews on Technology Needs
					A.1.4	Technology and Industry Workshops
					A.1.5	NASA TU Program
					A.1.6	Identify Presently Used Technologies
					A.1.7	Preliminary Estimates of Impact
					A.1.8	Select Appropriate Technology Needs
			A.3	Identify NASA Technology	A.2.1	Search Aerospace Technology Data Base through IAC
					A.2.2	Prepare Problem Statements
					A.2.3	Distribute Problem Statements through TUO's
					A.2.4	Contract Field Center Scientists and Engineers
					A.2.5	Contract Program Office Managers
			A.4	Evaluate Potential Solutions Incorporating NASA Technology	A.3.1	Review with Problem Originators
					A.3.2	Review with Technical Experts
					A.3.3	Review with TUO and Field Center Scientists and Engineers
					A.3.4	Select Commercialization Opportunities and Obtain TUO Approval
	B.0	Screening	B.1	Patent Search, Waivers, Licensing		
			B.2	Estimate Impact of Commercialization	B.2.1	Develop Impact Model
					B.2.2	Estimate Production Cost
					B.2.3	Preliminary Market Study
					B.2.4	Document Other Benefits
					B.2.5	Document Impact
			B.3	Technical Feasibility	B.3.1	Technology Gaps
					B.3.2	Scientific and Technical Uncertainties
					B.3.3	Estimated Product and Process Performance
			B.4	Identify Potential Manufacturers	B.4.1	Advisory Panels
					B.4.2	Industry Associations
					B.4.3	Industry Data Base
					B.4.4	Contact Firms
			B.5	Identify Manufacturer Qualifications	B.5.1	Government Industry Cooperation
					B.5.2	Technological Resources
					B.5.3	Confidentiality
					B.5.4	Financial Resources
					B.5.5	Product Line
					B.5.6	Marketing and Distribution

TABLE 6.- Concluded.

Level 1	Level 2	Level 3	Level 4
		B.6 Sources of Cofunding for Applications Engineering	B.6.2 Federal Agencies
			B.6.1 Industry and Industry/ Associations
			B.6.3 Market Protection
			B.6.4 Venture Capitalists
	C.0 Develop Commercialization Strategies	C.3 Assist in Development of Applications Engineering Project Plan	C.3.1 End Item Functional Requirements
			C.3.3 Applications Engineering Project Statement of Work
			C.3.4 Cost Estimates
			C.3.2 Tests, Evaluation, and Data Collection Requirements
		C.5 Develop and Document Cofunding Plan	C.5.1 Identify Potential Sources of Cofunding in Industry and Government
			C.5.2 Document Cofunding Mechanisms
		C.1 Document FDA and Other Regulatory Agency Requirements that Apply	
		C.6 Document Potential Manufacturers and R, D, and E Organizations for Performing Applications Engineering	
		C.4 Document Options for Providing Market Protection to Firms Investing in Commercialization	C.4.1 Patents, Patent Waivers, and Licensing
			C.4.2 Confidentiality
			C.4.3 Product Introduction Lead Time
		C.2 Market Development Strategy	C.2.1 Product and Process Acceptance
			C.2.2 Distribution System
	D.0 Task and Project Liaison		
	E.0 Records Maintenance		

in the past year to identify opportunities for NASA technology transfer. These include organizations such as the Society for Manufacturing Engineers (SME) and its daughter organizations the Robotics Institute of America, the National Machine Tool Builders Association, the American National Standards Institute, and the National Electrical Manufacturers Association. These associations are currently emphasizing automation and robotics as a first priority for their members. These associations provide opportunities for NASA to address broad segments of U.S. industry. For example, SME is currently preparing or planning (1) a 1985 *Directory of Manufacturing Research Needed by Industry* for all members and other requesters, (2) a feature issue of *Manufacturing Engineering* on "Manufacturing for and in Space," and (3) an ad hoc committee on space manufacturing applications. The NASA Applications Team has been invited to participate in all of these activities.

The second activity in this phase is the identification of applicable NASA technology through several mechanisms including the distribution of Problem Statements to Technology Utilization Officers (TUO's) at each NASA center. Each TUO is responsible for distributing the Problem Statements to the appropriate NASA scientists and engineers and forwarding their solutions back to the Applications Team for review with the problem originator.

Participation by the Applications Team in automation and robotics advisory panel or review meetings, as well as presentations of developing NASA technology, could efficiently expedite technology transfer. Such participation would increase Applications Team awareness of NASA automation and robotics participants and technology and would allow more expeditious technology transfer.

Screening. A match between an industry need and a technology represents a commercialization opportunity. The Applications Team facilitates the screening of the opportunities to assess the technical and commercial feasibility of the proposed solution. Patent and licensing options must be reviewed by the Applications Team in preparation for commercialization discussions with potential manufacturers. The Applications Team discusses the potential project with Federal agencies, industry, and industry associations to determine their interest in participation and cofunding.

Develop Commercialization Strategies

The strategy for successful technology transfer must consider product development and marketing factors, device evaluation, regulatory agency impact, acceptance by the user community, and the identification of funding sources for all phases of the project. The Applications Team works closely with the NASA Field Center to develop an applications engineering project plan including milestones and budget for the engineering development project.

An important NASA requirement for proceeding with a technology transfer project is the allocation of substantial cofunding from the manufacturer and/or other Federal agencies. The Applications Team assists NASA in the development and implementation of a plan for obtaining these cofunding commitments. In addition, the Team will prepare a list of potential manufacturers and assist NASA in the preparation of a plan for the selection of a manufacturer.

The NASA Applications Team will serve as an important resource in NASA's efforts to expedite the transfer of Space Station automation and robotics technology to U.S. industry. The Team will work with the automation and robotics program to facilitate interaction with industry associations, manufacturers, and other Federal agencies through existing Applications Team networks and mechanisms. In addition, the Applications Team's technology transfer activities in medicine and rehabilitation will facilitate the identification of possible opportunities to transfer Space Station automation and robotics technology to these areas.

Automation and Robotics Technology Transfer: A Case Study

NASA efforts in the transfer of automation and robotics technology to improve American

industrial productivity predates the current Space Station program. As part of the current NASA Technology Utilization (TU) program, a number of different automation and robotics technology transfers are in different stages of implementation. One good example of an automation and robotics technology transfer project is the robotic vision project at Johnson Space Center. This section describes this project's history as a case study to illustrate the active technology transfer methodology. This methodology consists of the following primary steps:

Identify Commercialization Opportunity

* Define the technology need

* Identify the applicable NASA technology

Screening

* Evaluate candidate solutions

Develop Commercialization Strategies

* Develop project plan

* Implement and monitor the project

The technology need for improved robotic vision was identified by the NASA Applications Team at the Research Triangle Institute. In robotic material handling applications, the robotic vision system is presented with a view of manufactured parts in random orientations and attitudes. The problem for the robotic vision system is to distinguish between unique parts and determine the attitude of a given part. Once this information has been determined, the robot's control computer plans a trajectory for picking up a part from the right direction. Most current robotic vision systems are based on the digital image processing of two-dimensional images captured with various electronic camera systems. Historically, these techniques have been impractically slow, although new algorithms and custom serial processing hardware are making the vision speeds sufficiently fast to make robotic material handling practical in the factory. Other industrial applications that could benefit from an improved robotic vision system include robotic assembly of electronics and automobiles and automated inspection. Arthur D. Little's Robotics Study Group estimates that the robotic market will grow from $250 million in 1983 to over $1 billion by 1987 with over half of the installations requiring vision capabilities. The Yankee Group of Boston has targeted general part inspection and identification as an even greater market for optical pattern recognition in a computer vision market they estimate to grow from $42 million in 1983 to more than $342 million in 1987.

NASA technology at Johnson Space Center was identified by the Technology Utilization Office and the Applications Team as a potential solution to the requirement for improved robotic vision. Many future NASA Shuttle and Space Station applications such as soft docking, on-orbit assembly and construction tasks, satellite retrieval, and station-keeping operations, have a need for an improved optical pattern recognition system. The heart of this type of system is a programmable mask and associated software for high-density storage and correlation of reference images. The Microwave and Laser Section of the Tracking and Communications Division of JSC has been responsible for the development of all optical pattern recognition devices for use in space applications. This group has been responsible for the development of programmable mask technology as part of the NASA-wide Optical Processing Working Group. A major thrust of this work has been in applications of real-time optical Fourier transform processing in optical correlators and pattern recognition systems. The techniques developed by this group and the experience gained in working with past generations of these devices are directly applicable to industrial uses of optical pattern recognition.

The potential solution was evaluated by industry and U. S. Army engineers from Redstone Arsenal who were also seeking improved robotic vision systems. Their enthusiastic reviews resulted in a meeting of Texas Instruments, the U. S. Army, the Applications Team, and NASA representatives at Johnson Space Center to discuss a collaborative project.

A project plan for the robotic vision project was developed and agreed upon by all the participants. This plan defines the project tasks, individual and organizational responsibilities, management plan, budget, and cofunding plan. The cofunding plan for the project is presented in the following table.

	FY85	FY86	FY87
NASA Technology Utilization	$ 50K	$ 115K	$ 50K
NASA OAST	$200K	$ 200K	$200K
U. S. Army	$170K	$ 250K	$250K
Texas Instruments	$625K	$1000K	$750K

The project plan was implemented in December 1984. The plan's milestones and budget will provide the basis for quarterly project monitoring.

POTENTIAL CONTRIBUTIONS TO INDUSTRY

If industry's needs are addressed in the Space Station design process and an effective program of technology transfer is pursued, what are some of the possible benefits to U.S. industry? In this section we look at some automation needs in today's industries and some of the anticipated advances in automation and robotics in the Space Station program and try to see what impact these new automation and robotics technologies might have on industry. The discussion is not intended to be exhaustive, but rather illustrative of some things which could reasonably be expected to happen.

Need for Advanced Automation in Industry

Automation and robotics are starting to make significant inroads into U.S. industry. By the end of this decade, General Motors expects to have as many as 20,000 industrial robots operating in its automotive assembly plants. In addition to General Motors, Ford expects to have about 10,000 and Chrysler about 5,000 industrial robots. Although these numbers represent the current growth in the market for industrial robots, they do not accurately reflect the potential demand for such advanced factory automation. Most of today's robots are being purchased to fill welding and spray-painting applications, which are only two of several major catagories of robotic applications. The main reason for their being so popular is the fact that the technologies needed to address them were the ones which matured first. Other applications, especially those involving assembly operations, require adaptive control technologies, which are still embryonic. Thus, the current state of the art in automation and robotics must undergo significant advancement before the majority of industrial applications for A&R can be satisfied.

One of the best examples of the basis for the need for adaptive control is small parts assembly and inspection. Most small batch assembly operations are done by human hands because, without adaptive control, industrial robots have to have the parts presented to them in a predetermined manner. Even with machine vision and tactile feedback, robots must be able to reason in order to understand what they see and feel and to deal with the real world. That is why most of the progress being made today in adaptive control remains in the laboratory and not in the factory.

There are many contributing factors to the continued growth in the demand for advanced factory automation and, therefore, for adaptive control. The two most important reasons are rising labor costs and the need for improved quality control. Rising labor costs, coupled with generally decreasing costs for electronic hardware, are making factory automation more cost effective. Improved quality control is one means of increasing productivity, which is necessary for competing with foreign manufacturers.

NASA's Role in Providing Advanced Automation

While the need for advanced automation technology in industry is evident, the means of satisfying the need are not certain. There needs to be a well-funded, interdisciplinary, coordinated R&D program in A&R. There is also a need for providing low-cost technology to small business, which cannot afford the kind

of advanced technologies being purchased by large corporations and the military.

The requirements for advanced automation and robotics on the Space Station will provide NASA with the opportunity to assume a leadership role in automation and robotics development. NASA is in a better position to accelerate such advancement than is industry because of several advantages NASA has in its ways of supervising and directing such development work. NASA has the unique ability to bring together various aspects of industry in a cooperative manner and get them to work with each other and share technology. Because such cooperation means less duplication of work, the costs associated with a joint effort are lower than those associated with uncoordinated effort. Since communication between coordinated development teams decreases the time associated with technological achievements, the goals are reached sooner than would be met in a competitive industrial environment.

In order to meet the requirement for autonomy for the Space Station, advancements in several technologies will be necessary. Adaptive control is one such technology which will have to be significantly advanced. Intelligent, general-purpose robots could play an important role in achieving autonomy for the Space Station, and the major technological challenge in building such a robot does not concern hardware, but software. Robots have been demonstrated in laboratory settings equipped with stereo vision, tactile feedback, and even voice I/O. However, these laboratory models are not capable of the adaptive control required by factory applications, especially assembly operations. Also, very little research has been conducted using dual-arm robots and even less with an AI robot controller, planning the robot's moves and dealing with the unexpected. The use of CAD technology, including data bases containing parts design information, have yet to be fully exploited in A&R research and development, especially in teaching a robot about its environment and how to perform its tasks. In other words, the hardware is available to meet the challenge of Space Station A&R, but the software is severely lacking. Therefore, the greatest contribution to industry from NASA's A&R research and development effort is most likely to be advanced software and the knowledge of how to apply it in a cost-effective manner.

Adaptive control technology developed for an intelligent robot on the Space Station could be transferred to industries on Earth by using the established NASA technology transfer mechanisms. NASA publications could be utilized to announce the development of the technology. The Corporate Associates Program could sponsor seminars to present the technology to high-level industry representatives. Software could be made available through COSMIC. The Technology Applications Team could identify the commercial opportunities for adaptive control, perform a market analysis, and evaluate the feasibility of adapting the technology for use in industry. If appropriate, an applications engineering project would be undertaken to implement the transfer operation, thus ensuring the availability and usability of the technology for industry.

Impact on Industry

What would be the potential impact of adaptive control on industry? As mentioned earlier, one area where adaptive control would have immediate impact is small parts assembly and inspection. Since assembly applications constitute about one-third of the total potential applications for industrial robots, the impact of adaptive control could be extensive.

In a study performed by Neil Digeronimo of the Cleveland International Research Institute (CIRI), robotic sales were predicted for the year 2000 under two scenarios: (1) a significant NASA development effort in robotics and artificial intelligence begins in 1985 and continues through IOC; (2) no NASA effort occurs. Without NASA effort robotic sales in assembly and inspection operations were predicted to be $2.1 billion and with NASA effort, $2.9 billion, or an increase of 38 percent due to the NASA effort.

In addition to assembly applications, repair and service applications are likely to be affected by the availability of adaptive

control. While repair and service tasks would require the ultimate in advanced automation and robotics technology, adaptive control would be a key element in meeting the technological requirements. Since service and repair functions make up 80 percent of the tasks in U.S. industries which use hard automation, there is potentially a very large market for robots which can perform repair and service functions. If the United States could develop such robotic capability before our foreign competitors, we would have a great advantage in the world marketplace.

If, in addition to adaptive control, we assume other needed artificial intelligence methods become developed sufficiently to achieve complete autonomy in a space robot by the year 2000, what would be some potential impacts on industry? One effect would be to significantly reduce the time scale for achieving completely autonomous robotic systems. Perhaps the greatest potential gain from such a development would be the advantage U.S. industries could have in robotic repair and service applications.

Another effect, assuming the technology were made readily available to industry, would be a dramatic increase in U.S. sales of industrial robots. Under this assumption, Digeronimo projected that sales would double the original prediction by the year 2000.

There are many other automation and robotics technologies besides the ones mentioned thus far in this section which may be developed for the Space Station. The potential applications for these technologies in industry are many and varied. Rather than attempt to discuss all such technologies and their applications, table 7 is included here to present a more extensive (but still incomplete) list of potential technologies to be developed for the Space Station and their applications in industry. A technology checked off corresponding to a given application indicates a technology which is expected to be significant for that application. Other unchecked technologies may also be applied, but they are seen as being less essential for the application. Many existing technologies which are not listed would also be required for various applications.

TABLE 7.- POTENTIAL TECHNOLOGIES DEVELOPED FOR THE SPACE STATION AND THEIR APPLICATIONS

Potential Technologies	Applications										
	Assembly	Maintenance & Repair	Product/ Process/ Structure Inspection	Plant/ Facility Security	Factory Control	Transporting & Handling Toxic Materials	Pruning, Picking, & Cultivating Agricultural Crops	Medical Surgery	Computer Communi-cations	Go-fer for Disabled	Fire Fighting
Hybrid Robot/ Teleoperator	X	X	X	X		X	X	X		X	X
Adaptive Control	X	X	X	X		X	X	X		X	X
Off-Line Robot Programming Through CAD/CAM Technology	X	X	X								
Tactile Sensors (Arrays, Force Feedback)	X	X	X	X			X	X		X	
Advanced Machine Vision (3D-Scene Analysis)	X	X	X	X			X			X	X
Mobile Robot Guidance/Navigation		X		X		X	X			X	X
Advanced Planning for Robotics	X	X	X	X		X	X			X	X
Dual Arm Robotics	X	X				X				X	X
Dextrous Manipulator	X	X	X				X	X		X	
Robot Application Modeling by Visual Simulation	X	X				X	X	X			X
Diagnostic Expert System		X	X	X	X						X
Distributed Computing		X			X				X		
Advanced Data Storage Technology		X	X	X	X				X		
Intelligent Man/ Machine Interfaces	X	X	X	X		X		X		X	X
Intelligent Remote Sensor Technology		X	X	X	X						X
Energy Management/ Advanced Process Control Technology					X						
Advanced Fault-Tolerant Disciplines		X			X				X		

Chapter 8

COMMERCIALIZATION ACTIVITIES ON THE SPACE STATION

In this chapter we discuss the importance of developing the commercial opportunities of space, what NASA's policy is toward commercial activity in space, the special opportunities afforded by the Space Station, and how advanced automation and robotics on the Space Station will facilitate commercial ventures in space. All statements of NASA policy in this chapter are taken from the recently published *NASA Commercial Space Policy* (NASA, 1984a) and are a restatement of existing policy.

IMPORTANCE OF SPACE COMMERCIALIZATION

The call to pursue the commercial opportunities of space has been voiced repeatedly over the past few years by a number of Government and scientific sources. Here are some of the statements which have been issued.

"The United States Government will provide a climate conducive to expanded private sector investment and involvement in civil space activities...."

- President Ronald Reagan
National Space Policy
July 4, 1982

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"We should establish a policy which would encourage commercialization of space technology to the maximum extent feasible."

- Committee on Science and Technology
U.S. House of Representatives Report
April 15, 1983

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"The Committee is fully supportive of efforts by the private sector to invest and seek commercial opportunities in space."

- Committee on Commerce, Science and Transportation
U.S. Senate
Report May 16, 1983

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"The extent to which past investment in space technology contributes to our future economic well-being and national growth will depend in large measure on policies and actions taken in a spirit of collaboration by the Federal Government and industry.

"Unless the public and private sector join to develop the opportunities presented by new space technologies and unless entrepreneurial forces are engaged more fully, the United States will fall behind in the contest for leadership in space and the economic rewards associated with that position."

- National Academy of Public Administration
May 1983 Report

In mid-1983 NASA formed a task force for the purpose of examining the opportunities for and impediments to commercial activities in space. Their conclusions were

* Commercial activities in space by private enterprise should be expanded now if our nation is to retain and improve its leadership in science and technology, its high living standards, and its advantage in international trade.

* Natural and bureaucratic barriers inhibiting the commercialization of space need to be and can be lessened or removed through joint actions by the Government and private enterprises.

* With firm resolve and the commitment of reasonable resources over a number of years, Government and private enterprise working together can turn space into a realm of immense benefit for our nation.

* A positive NASA Commercial Space Policy should be implemented to expedite the expansion of self-sustaining profit-earning tax-paying jobs-providing commercial space activities.

NASA's thrust into the future is taking a new turn: NASA is inviting free enterprise to participate in space. NASA is encouraging industries and other private entities to finance and conduct business in space.

Private investment in space is called "space commercialization." Commercial projects would aim at developing profitable products and services. Envisioned are industries turning out useful goods for sale to consumers and industrial customers on Earth.

Stimulating the commercialization of space will give new impetus and importance to traditional space efforts. The rewards can be immense.

NASA has accumulated a long and proud history of working closely and productively with private enterprises. Sometimes likened to a tower on three pedestals, NASA space programs have been based on participation and contributions by a trio of segments in our society - Government, industry, and academic institutions.

Since its earliest days, NASA has employed industries and universities as contractors. NASA was the customer. The other partners were the suppliers. Project Apollo, history's largest engineering project, was an example of this three-way partnership.

Since 1962 NASA has provided launch services for commercial communications satellites. Beginning in 1972, NASA entered into "partnership" arrangements with private firms for the commercial use of space. Now, the nature and character of NASA's relationship with private enterprise is changing still more. To persuade private investors to become involved in new space endeavors, NASA must be responsive to the needs and wants of these investors.

NASA must assure these investors of reliable and dependable roundtrip transportation for their projects between Earth and orbit. NASA must also help assure the availability of suitable work places for industries in orbit.

Space commercialization may turn out to be less headline-catching than were the landings by men on the Moon in the late 1960's and early 1970's. But major endeavors by private enterprise in space are likely to make the 1980's and 1990's just as exciting and spectacular.

Moreover, space commercialization can have profound impact on the future of our nation. We already know from our experiences with highly profitable, privately owned communications satellites that free enterprise in space works well. New leaps in technology which may emerge from private initiatives in space could have major implications for the national economy, individual living standards and life styles, industrial activities and jobs, and international trade. Outer space appears destined to become a major arena of international technological and commercial rivalry. The United States cannot ignore the competition from abroad if it wants to retain its preeminence. NASA, as a lead agency for advanced technology, must accept the challenge. NASA must reshape and reorient itself to accommodate and spearhead the new National needs and goals.

NASA COMMERCIAL SPACE POLICY

In response to the need for formulating an enlightened and aggressive approach to space commercialization, representatives from NASA Headquarters and Field Centers have drawn up the NASA Commercial Space Policy. These representatives looked at the

commercial possibilities in space and how NASA can encourage more private industrial ventures in space. To supplement their perspective, the NASA representatives sought and received advice from experts in industry and universities as well as other outside specialists.

Goals and Principles

The primary goal of NASA's Commercial Space Policy is to encourage and stimulate free enterprise in space.

Private investments in space, in turn, are expected to (a) yield important economic advantages, (b) advance science and technology, (c) help maintain U.S. space leadership, and (d) enhance the nation's competitive position in international trade, thereby improving the U. S. balance of payments.

Implementation of the NASA Commercial Space Policy is to be guided by these five principles:

(1) The Government should reach out to and establish new links with the private sector.

NASA will expand its traditional links with the aerospace industry and the science community to include relationships with major nonaerospace firms and new entrepreneurial ventures, as well as with the financial and academic communities.

(2) Regardless of the Government's view of a project's feasibility, it should not impede private efforts to undertake commercial space ventures.

If the private sector is willing to make the necessary investment, the feasibility of a project should be determined by the marketplace and the creativity of the entrepreneur rather than the Government's opinion of its viability.

(3) If the private sector can operate a space venture more efficiently than can the Government, then such commercialization should be encouraged.

When developing new public space programs, the Government should actively consider the view of, and the potential effect on, the private sector.

(4) The Government should invest in high-leverage research and space facilities which encourage private investment. However, the Government should not expend tax dollars for endeavors the private sector is willing to underwrite.

This will provide at least two benefits. First it will enable NASA to concentrate a greater percentage of its resources on advancing the technological state of the art in areas where the investment is too great for the private sector. Second, it will engage the private sector's applications and marketing skills for getting space benefits to the people.

(5) When a significant Government contribution to a commercial endeavor is requested, two requirements must be met. First, the private sector must have significant capital at risk, and second, there must be significant potential benefits for the nation.

In appraising the potential benefits from and determining appropriate Government contributions to commercial space proposals, NASA will utilize an equitable, consistent review process.

A possible exception to these principles would be a commercial venture intended to replace a service or displace a NASA R&D program and/or technology development program of paramount public importance now provided by the Government. In that case, the Government might require additional prerequisites before commercialization.

Implementation

In implementing this policy, NASA will take an active role in supporting commercial space ventures in the following categories, listed in order of importance:

* New commercial high-technology space ventures

* New commercial applications of existing space technology

* Commercial ventures resulting from the transfer of existing space programs to the private sector

NASA will implement initiatives to reduce the technical, financial, and institutional risks associated with doing business in space.

To reduce technical risks, NASA will

Support research aimed at commercial applications opportunities; ease access to NASA experimental facilities; establish scheduled flight opportunities for commercial payloads; expand the availability of space technology information of commercial interest; and support the development of facilities necessary for commercial use of space.

To reduce financial risks, NASA will

Continue to offer reduced-rate space transportation for high-technology space endeavors; assist in integrating commercial equipment with the Shuttle; provide seed funding to stimulate commercial space ventures; and, under certain circumstances, purchase commercial space products and services and offer some exclusivity.

To reduce institutional risks, NASA will

Speed integration of commercial payloads into the Orbiter; shorten proposal evaluation time for NASA/private sector Joint Endeavor proposals; establish procedures to encourage development of space hardware and services with private capital instead of Government funds; and introduce new institutional approaches for strengthening NASA's support of private investment in space.

The Commercial Development Division has been established within the Office of Commercial Programs at NASA Headquarters to coordinate commercial space matters. NASA Field Centers will participate in both the development and operational phases of the program. The program will identify space commercialization opportunities and industries suitable for developing these opportunities and will establish the means to make potential space investors aware of these opportunities.

COMMERCIALIZATION OPPORTUNITIES ON THE SPACE STATION

The Space Station will provide an unparalleled opportunity for space commercialization. For the first time there will be a permanent station in space with both manned and unmanned elements. The Space Transportation System will make the Space Station accessible for supplying raw materials and equipment and for returning finished products.

Advantages Offered by the Space Station

A variety of unique conditions will be provided by the Space Station for commercial use. These include, at least

* Microgravity

* High vacuum

* Isolation from disturbance and contamination

* An abundance of cosmic ray primaries

* A synoptic view of Earth

The advantages of these conditions can be considerable, depending on the application. For example, General Electric has examined the possibility of growing crystals of gallium arsenide by an electroepitaxial process in space, and has estimated that the yield for the highest level of quality could be increased from only about 1 percent on Earth to as much as 70 percent in space, resulting in substantial cost savings.

The Space Station will provide commercial firms with the opportunity to carry out a variety of endeavors in space. These include

* Experimental work of many kinds

* Manufacturing processes; e.g., crystal growth and production of ultrapure pharmaceuticals

* Assembly of large-scale space structures

* Satellite assembly, repair, and maintenance

Other applications are possible in the more distant future, such as using the Space Station as a base for lunar mining or planetary exploration and colonization.

Some specific applications which have been considered for Space Station include

* Stereoscopic imaging system for Earth observation

* Hydroponic plant growth

* Material processing, such as

  - Gallium arsenide processing

  - Mercury cadmium telluride processing

  - Magnetophoresis separation

* Solar optical telescope

* Electrophoretic separation of biologicals

* Microelectronics chip production

* Large structure fabrication

Enhancing Commercial Opportunities

Commercialization opportunities on the Space Station can be enhanced in a number of ways. One way is by making the Space Station an accessible laboratory for the development and testing of new products for a large base of users (i.e., small, as well as large, industries). Therefore, it is desirable to establish a mechanism within NASA whereby a small business with limited financial resources could utilize the Space Station. At one time, the Advanced Applications Flight Experiment (AAFE) office at LaRC provided support for small business to propose and conduct system flight experiments. Possibly, this concept could be resurrected and applied to promote wider use of the Space Station. Two elements are critical to making such a program work. First, submittals should be accepted on a regular schedule, at least yearly, so that companies can plan ahead and be assured their proposals will be considered. Secondly, there should be designated points of contact within NASA that these companies can approach at any time.

As an example, consider a small business concern that wants to test an innovative man/machine interface using the various workstations and advanced systems onboard the Space Station. Results of the system test might indicate that the product is superior to existing versions. In such a case NASA would adopt the technology for its own applications, while the business would be allowed to market the product for use in terrestrial applications, thereby effecting a bidirectional transfer of technology.

Another way to encourage participation of small businesses is through the Small Business Innovative Research Program (SBIR). In this program proposals from businesses are solicited in a large number of space-related areas. If separate sections in the Announcement of Opportunity were devoted to artificial intelligence and to robotics/teleoperations with sufficient funding to support a large number of research projects, more small businesses would be able to try out innovative ideas in automation and robotics. Such new ideas are essential to advancing the state of the art to meet Space Station requirements beyond IOC.

Another means of enhancing commercial opportunities on the Space Station is by simplifying and speeding up the process of integrating commercial payloads. Several steps could be taken to accomplish this goal.

* Assigning a payload support group to work in partnership with the private investor to assist in all integration activities

* Standardizing and maximizing the number of locations on the Space Station to which commercial payloads could be integrated

* Assuring the availability of pallets and other equipment carriers and pressurized modules for simplified interfaces

* Allowing the commercial partner to establish its own acceptable payload risk levels

ROLE OF AUTOMATION IN SPACE COMMERCIALIZATION

Automation is a key element in the successful commercialization of space. In a general sense, automation will make the Space Station a better environment for support of commercial ventures. Automation can help reduce the costs of operating the Space Station, which will in turn affect the rates the Government will have to charge private industry for using Space Station facilities. Automation will increase productivity on the Space Station, making commercial manufacturing operations more productive. The safety of the crew and the station itself will be enhanced by automated fault diagnosis and recovery systems. Fault-tolerant, highly reliable computing facilities will ensure effective collection of experimental data and support for manufacturing processes.

Specific applications will rely on automation for different reasons. Many applications would not be feasible in space without automation. Automation allows manufacturing or experimental activities to occur without constant attendance by humans. Automation can make possible operations which might otherwise be dangerous or undesirable for humans to perform. Some manufacturing processes involve handling hazardous materials or produce toxic products. Growing gallium arsenide crystals is one example. Certain manufacturing processes involve very precise, repetitive cutting, shaping, or welding operations which are more effectively performed by machines than by humans. Automation will be necessary to support any experiments or Earth-viewing operations which require the use of platforms distant from the Space Station itself. Expert systems for process control will be used to control manufacturing operations.

Flexible, intelligent teleoperation and robotics systems will provide support to a variety of commercial activities in space. They can be used for materials handling in manufacturing. They will be essential for any large-scale construction in space. A study by TRW (TRW, 1984) details the need for teleoperations and robotics in satellite servicing. Flexible, automated systems can be used to service a variety of spacecraft, economically and effectively. A general-purpose robot could also be used to retrieve film or otherwise service an Earth-viewing satellite in geosynchronous orbit. Remote manipulators will be used to deploy and retrieve experiment packages at the Space Station.

The commercial utilization of space is a high-priority item in our overall space program. The Space Station will provide unique opportunities to realize this goal. The automation technology being developed for the Space Station will play a key role in making space commercialization a success.

REFERENCES

Alexander, T. (1982). "Teaching Computers the Art of Reason," Fortune, May 17.

Andrews, Harold L. (1984). "Speech Processing," Computer, Vol. 17, No. 10, pp. 315-324.

Bell, D. (1976). The Coming of Post-Industrial Society, Basic Books, New York, N.Y.

Boeing (1984). "Space Station Automation and Robotics Study, Operator-Systems Interface," D 483-10027-1, November.

Booch, Grady (1983). "Software Engineering with Ada," Benjamin/Cummings Publ. Co. Inc., Menlo Park, CA.

Buchanan, B. G. and E. A. Feigenbaum (1978). "DENDRAL and Meta-DENDRAL: Their Applications Dimension," Artificial Intelligence, Vol. 11, pp. 5-24.

CARAI (1983). "Applications of Robotics and Artificial Intelligence to Reduce Risk and Improve Effectiveness," Committee on Army Robotics and Artificial Intelligence, Manufacturing Studies Board, NRC, National Academy Press, Washington, D.C.

CCCI (1984). "Computer Integration of Engineering Design and Production: A National Opportunity," Committee on the CAD/CAM Interface, Manufacturing Studies Board, NRC, Washington, D.C.

CJEC (1982). "Robotics and the Economy," Congressional Joint Economics Committee, Washington, D.C.

Computer (1984). IEEE Computer Society, Vol. 17, No. 10, October Issue, IEEE Centennial Issue on The State of Computing.

DARPA (1983). "Strategic Computing," Department of Defense, Washington, D.C.

Denver Research Institute (1979). NASA Technology Utilization Program: A Cost-Benefit Analysis, Denver, Colorado, February.

Dorros (1983). "Telephone Net Go Digital," IEEE Spectrum, April.

Easter, Robert W. and Robert L. Staehle (1984). "Space Platforms and Autonomy," JPL D-1973, November.

Evans, D. D. and R. R. Gajewski (1985). "Expanding Role for Autonomy in Military Space," Aerospace America, February.

Fagan, L. M., J. C. Kunz, E. A. Feigenbaum, and J. Osborne (1979). "Representation of Dynamic Clinical Knowledge: Measurement Interpretation in the Intensive Care Unit," Sixth International Joint Conference of Artificial Intelligence.

Feigenbaum, E. A. and P. McCorduck (1984). The Fifth Generation: Artificial Intelligence and Japan's Computer Challenge to the World, New American Library, New York, N.Y., p. 11.

Fordyce, J. S. and Schwartz, H. J. (1984). "The Potential Impact of a New Power System Technology on the Design of a Manned Space Station," NASA TM 83770: Lewis Research Center, Cleveland, Ohio.

Fox, J. C., (1983). "Study of Robotics Systems Applications to the Space Station Program," Report KTR-108, KMS Fusion, Inc., Ann Arbor, MI.

Freeman, P. (1980). "STS Workday Handbook," NASA Johnson Space Center, Operations Planning Section, February.

Freitas, R. A. and W. P. Gilbreath, eds. (1982). "Advanced Automation for Space Missions," NASA Conference Publication 2255.

Fu, K. S., and Azriel Rosenfeld (1984). "Pattern Recognition and Computer Vision," Computer, Vol. 17, No. 10, pp. 274-282.

General Electric (1984). "Space Station Automation Study--Automation Requirements Derived from Space Manufacturing Concepts," Vol. I, II, Contract NAS5-25182, November.

Gevarter, W. B. (1983). "An Overview of Artificial Intelligence and Robotics Volume I - Artificial Intelligence Part A-The Core Ingredients," NASA TM-85836.

Griffin, G. D. (1984). "Contractor and Government: Teamwork and Commitment," Proceedings of the NASA Symposium on Productivity and Quality, Washington, D.C., September 25-26, 1984. U.S. GPO.

Harmon, Leon D. (1984). "Automated Tactile Sensing," International Journal of Robotics Research, Vol. 1, No. 2.

Hayes-Roth, Frederick (1984). "Knowledge-Based Expert Systems," Computer, Vol. 17, No. 10, pp. 263-273.

Hendricks, H. D. and N. D. Murray (1983). "Wavelength Division Multiplexing for Future Space Station Data Systems," Proceedings of SPIE, San Diego, California.

Hillis, W. D. (1982). "A High-Resolution Imaging Touch Sensor," International Journal of Robotics Research, Vol. 1, No. 2, Summer.

Hughes Aircraft Company (1984). "Automation Study for Space Station Subsystems and Mission Ground Support, Final Report," Hughes Ref. No. F5713, Contract 82-14F, November.

Jarvis, John F. (1984). "Robotics," Computer, Vol. 17, No. 10, pp. 283-292.

Jensen, E. D. and N. Pleszkock (1984). "ARCHOS: A Physically Dispersed Operating System," IEEE Distributed Proc. Tech. Committee Newsletter, June.

JPL (1984). "Autonomous Systems: Architecture and Technology," JPL D-1656, August.

Kaplan (1984). "Japan Information Network System," IEEE Spectrum, May.

Keebach, T. J. (1984). "Programmable Position Control Uses Standard Induction Motor as Servo," Control Engineering, Vol. 31, No. 1, pp. 108-110.

Leontief, W. and F. Duchin (1984). "Service and Manufacturing Sector Labor Impact of Computer-Based Automation," Institute for Economic Analysis, New York University, New York.

Lippiatt, Thomas F. and Donald Waterman (1985). "Potential Applications of Expert Systems and Operations Research to Space Station Logistics Functions," Rand Report WD-2515-NASA, January.

Loftus, Joseph P. (1983). "An Historical Review of NASA Manned Spacecraft Crew Stations." Conference on Aerospace Crew Station Design, sponsored by the International Center for Transportation Studies, Amalfi, Italy, October [to be published in Journal of the British Interplanetary Society].

Martin Marietta (1984). "Space Station Automation Study - Autonomous Systems and Assembly," Vol. I, II, Contract NAS8-35042, November.

Mathtech (1977). A Cost-Benefit Analysis of Selected Technology Utilization Office Programs, Princeton, New Jersey, November.

McDermott, J. (1981). "R1: The Formative Years," AI Magazine, Vol. 2, No. 2, pp. 21-29.

McDonnell Douglas (1984). "The Human Role in Space," Vols. I, II, III, MDC H 1295, Contract NAS8-35611.

NASA (1984a). "NASA Commercial Space Policy," National Aeronautics and Space Administration, Washington, D.C.

NASA (1984b). "Space Station Program Description Document," Vols. 1-7, NASA TM 86652, NASA Scientific and Technical Facility, Baltimore, MD, March.

NASA (1984c). "Civil Applications of Space Nuclear Power - Final Report of the Civil Missions Advisory Group," NASA Headquarters, August.

NASA (1984d). "Space Station Reference Configuration Description," Johnson Space Center (JSC-19989).

NASA (1984e). "Space Station Definition and Preliminary Design Request for Proposal," RFP-9-BF-10-4-01P, September 15.

OTA (1982). "The Social Impact of Robotics," Office of Technology Assessment, Washington, D.C.

OTA (1984a). "OTA Workshop on Automated Space Station," Senate Hearings 98-889 Pt. 2 (pp. 803-1678) Department of Housing and Urban Development and Certain Independent Agencies Appropriations for FY 1985 H.R. 5713, pp. 1233-1351.

OTA (1984b). "Civilian Space Stations and the U.S. Future in Space," Office of Technology Assessment, OTA-ST1-241, Washington, D.C.

Proceedings of the International Conference on Fifth Generation Computer Systems (1982). Elsevier-North Holland, New York.

Raibert, M.H. (1982). "Design and Implementation of a VLSI Tactile Sensing Computer," International Journal of Robotics Research, Vol. 1, No. 3.

RISME (1984). "Bibliography of Robotic Technical Papers," Robotics International of the Society of Manufacturing Engineers, Dearborn, MI.

Robinson, A. L. (1984). "Powerful New Magnetic Material Found," Science, Vol. 223, No. 4639, pp. 920-922.

Rockmore, Joseph (1984). Personal communication, December 3.

Sacerdoti, E. D. (1977). "A Structure for Plans and Behavior," Elsevier Computer Science Library.

Sagan, C. (1980). "Machine Intelligence and Robotics: Report of the NASA Study Group," USGPO 1980-311-451/2659.

Shortliffe, E. H. (1976). Computer-Based Medical Consultation: MYCIN, American Elsevier, New York.

Snyder, Conway W. (1977). "The Missions of the Viking Orbiters," Journal of Geophysical Research, Vol. 82, No. 28, pp. 3971-3983.

Soffen, Gerald A. (1977). "The Viking Project," Journal of Geophysical Research Vol. 82, No. 28, pp. 3959-3970.

SRI International (1985). "NASA Space Station Automation: AI-Based Technology Review," to be published, Project 7268, Menlo Park, California.

Stonier, T. (1984). The Wealth of Information, Methuen London Ltd., London.

Taylor, William (1984). "Real-Time Parts Implosion, or - Why Automatic Factories Are Not," Programmable Controls, November-December, pp. 19-31.

TRW (1984). "Space Station Automation Study - Satellite Servicing," Vol. I, II., Contract NAS8-35081, November.

U.S. Congress (1976). Review of Intergovernmental Dissemination of Federal Research and Development Results. House Committee on Science and Technology, Committee Print, Special Oversight Report No. 5.

Van Colt, H. and Kinkade, R. (1972). Human Engineering Guide to Equipment Design, Joint Army, Navy, and Air Force Steering Committee, McGraw Hill, Revised edition.

Vere, S. (1983). "Planning in Time: Windows and Durations for Activities and Goals," Pattern Analysis and Machine Intelligence, Vol. 5, No. 3, May, pp. 246-266.

Von Tiesenhausen, G. (1982). "An Approach Towards Functional Allocations Between Humans and Machines in Space Station Activities," NASA Marshall Space Flight Center TM-82510, November.

Weiss, S. M. and C. A. Kulikowski (1981). "Expert Consultation Systems: The EXPERT and CASNET Projects," Machine Intelligence, Infotech State of the Art Report 9, No. 3.

ACRONYMS AND ABBREVIATIONS

A&R - Automation and Robotics

AC - Alternating Current

ACS - Attitude Control System

ADH - Advanced Development Hardware

AEC - Atomic Energy Commission

AI - Artificial Intelligence

ANSI - American National Standards Institute

AOS - Aquisition of Signal

ARC - Ames Research Center

ASCII - American Standard Code for Information Interchange

ASR - Automatic Speech Recognition

ATAC - Advanced Technology Advisory Committee

ATP - Authority to Proceed

BIBB - Bus Interface Building Block

BIU - Bus Interface Unit

C&T - Communications and Tracking

CAD - Computer Aided Design

CAE - Computer Aided Engineering

CAI - Computer Aided Instruction

CAM - Computer Aided Manufacturing

CCTV - Closed Circuit Television

CDR - Critical Design Review

CI - Customer Integration

CMDS - Commands

CMG - Control Moment Gyro

CSD - Contract Start Date

DARPA - Defense Advanced Research Projects Agency

DBMS - Data Base Management System

DDT&E - Design, Development, Test, and Evaluation

DMS - Data Management System

DOC - Department Of Commerce

DOD - Department Of Defense

DOE - Department Of Energy

DOF - Degrees Of Freedom

DR - Data Requirement

DTO - Detailed Test Objective

ECLSS - Environmental Control and Life Support System

EMI - Electromagnetic Interference

EMS - Engineering Master Schedule

EMU - Extravehicular Mobility Unit

EOS - Earth Observing System

EPS - Electrical Power System

ESS - Energy Storage Subsystem

EV - Extravehicular

EVA - Extravehicular Activity

FOC - Full Operational Capability

GaAs - Gallium Arsenide

GEO - Geosynchronous Earth Orbit

GFE - Government Furnished Equipment

GFP - Government Furnished Property

GN&C - Guidance, Navigation, and Control

GPS - Global Positioning System

GSE - Ground Support Equipment

GSFC - Goddard Space Flight Center

HMF - Health Maintenance Facility

ICD - Interface Control Document

IDMS - Information and Data Management System

IEEE - Institute of Electrical and Electronic Engineers

IGES - Initial Graphic Exchange Specification

IOC - Initial Operational Capability

IPS - Instrument Pointing System

IRD - Interface Requirements Document

IRR - Initial Requirements Review

ISR - Interim System Review

IV - Intravehicular

IVA - Intravehicular Activity

JPL - Jet Propulsion Laboratory

JSC - Johnson Space Center

KBPS - Kilobits Per Second

KIPS - Knowledge Information Processing Systems

KSC - Kennedy Space Center

LaRC - Langley Research Center

LeRC - Lewis Research Center

LIPS - Logical Inferences Per Second

LOS - Loss Of Signal

MBPS - Megabits Per Second

MDB - Master Data Base

MMU - Manned Maneuvering Unit

MPAC - Multipurpose Application Consoles

MS - Margin of Safety

MSFC - Marshall Space Flight Center

NASA - National Aeronautics and Space Administration

NHB - NASA Handbook

NMI - NASA Management Instruction

NSF - National Science Foundation

NSTS - National Space Transportation System

OAST - NASA Office of Aeronautics and Space Technology

OEA - NASA Office of External Affairs

OMV - Orbital Maneuvering Vehicle

ORU - Orbital Replaceable Unit

OSC - NASA Office of Space Commercialization

OSF - NASA Office of Space Flight

OSI - Operator/System Interface

OSS - NASA Office of Space Station

OSSA - NASA Office of Space Science And Applications

OSTDS - NASA Office of Space Tracking And Data Systems

OSTP - White House Office of Science And Technology Policy

OTV - Orbital Transfer Vehicle

PC - Personal Computer

PDR - Preliminary Design Review

PGS - Power Generation Subsystem

PL - Public Law

PMAD - Power Management and Distribution

POCC - Payload Operations Control Center

PRCB - Program Requirements Change Board

PWR - Space Station Power Subsystem

R&D - Research and Development

RCB - Requirements Change Board

RCS - Reaction Control System

RF - Radio Frequency

RFI - Radio Frequency Interference

RFP - Request For Proposal

RMS - Remote Manipulator System

ROV - Remotely Operated Vehicle

RTG - Radioisotope Thermoelectric Generators

SAR - Synthetic Aperture Radar

SDE - Software Development Environment

SDR - System Design Review

SE&I - Systems Engineering and Integration

SEB - Source Evaluation Board

SEC - Station Executive Controller

SI - International System of Units

SIR - Systems Integration Review

SOW - Statement of Work

SR&QA - Safety, Reliability, and Quality Assurance

SRR - System Requirements Review

SSDMS - Space Station Data Management System

SSDS - Space Station Data Systems

SSIS - Space Station Information System

SSP - Space Station Program

SSPE - Space Station Program Element

SSWP - Space Station Work Package

STD - Standard

STS - Space Transportation System

TBD - To Be Determined

TCS - Thermal Control System

TDASS - Tracking and Data Acquisition Satellite System

TDRSS - Tracking and Data Relay Satellite System

TLM - Telemetry

U.S. - United States

VHSIC - Very High Speed Integrated Circuits

VLSI - Very Large Scale Integration

WBS - Work Breakdown Structure

WP - Work Package

GLOSSARY

[This glossary was obtained from Gevarter, 1983.]

A

Activation Mechanism: The situation required to invoke a procedure - usually a match of the system state to the preconditions required to exercise a production rule.

AI Handbook: The Handbook of Artificial Intelligence, E.A. Feigenbaum, A. Barr and P.R. Cohen (Eds.). Published by W. Kaufmann, Los Altos, CA in 1981 and 1982. This important project was supported by DARPA and NIH.

Algorithm: A procedure for solving a problem in a finite number of steps.

AND/OR Graph: A generalized representation for problems reduction situations and two person games. A tree-like structure with two types of nodes. Those for which several successors of a node have to be accomplished (or considered) are AND nodes. Those for which only one of several of the node successors are necessary are OR nodes. (In about half the literature the labeling of AND and OR nodes is reversed from this definition.)

Antecedent: The left-hand side of a production rule. The pattern needed to make the rule applicable.

Argument Form: A reasoning procedure in logic.

ARPANET: A network of computers and computational resources used by the U.S. AI community and sponsored by DARPA (Defense Advance Research Projects Agency).

Artificial Intelligence (AI): A discipline devoted to developing and applying computational approaches to intelligent behavior. Also referred to as machine intelligence or heuristic programming.

Artificial Intelligence (AI) Approach: An approach that has its emphasis on symbolic processes for representing and manipulating knowledge in a problem solving mode.

Atom: An individual. A proposition in logic that cannot be broken down into other propositions. An indivisible element.

Autonomous: A system capable of independent action.

B

Backtracking: Returning (usually due to depth-first search failure) to an earlier point in a search space. Also a name given to depth-first backward reasoning.

Backward Chaining: A form of reasoning starting with a goal and recursively chaining backwards to its antecedent goals or states by applying applicable operators until an appropriate earlier state is reached or the system backtracks. This is a form of depth-first search. When the application of operators changes a single goal or state into multiple goals or states, the approach is referred to as problem reduction.

Blackboard Approach: A problem solving approach whereby the various system elements communicate with each other via a common working data storage called the blackboard.

Blind Search: An ordered approach that does not rely on knowledge for searching for a solution.

Blocks World: A small artificial world, consisting of blocks and pyramids, used to develop ideas in computer vision, robotics, and natural language interfaces.

Bottom-Up Control Structure: A problem solving approach that employs forward reasoning from current or initial conditions. Also referred to as an event-driven or data-driven control structure.

Breadth-First Search: An approach in which, starting with the root node, the nodes in the search tree are generated and examined level by level (before proceeding deeper). This approach is guaranteed to find an optimal solution if it exists.

C

Clause: A syntactic construction containing a subject and a predicate and forming part of a statement in logic or part of a sentence in a grammar.

Cognition: An intellectual process by which knowledge is gained about perceptions or ideas.

Combinatorial Explosion: The rapid growth of possibilities as the search space expands. If each branch point (decision point) has an average of n branches, the search space tends to expand as nd, as depth of search (d) increases.

Common Sense: The ability to act appropriately in everyday situations based on one's lifetime accumulation of experiential knowledge.

Common Sense Reasoning: Low-level reasoning based on a wealth of experience.

Compile: The act of translating a computer program written in a high-level language (such as LISP) into the machine language which controls the basic operations of the computer.

Computational Logic: A science designed to make use of computers in logic calculus.

Computer Architecture: The manner in which various computational elements are interconnected to achieve a computational function.

Computer Graphics: Visual representations generated by a computer (usually observed on a monitoring screen).

Computer Network: An interconnected set of communicating computers.

Computer Vision (Computational or Machine Vision): Perception by a computer, based on visual sensory input, in which a symbolic description is developed of a scene depicted in an image. It is often a knowledge-based expectation-guided process that uses models to interpret sensory data. Used somewhat synonymously with image understanding and scene analysis.

Conceptual Dependency: An approach to natural language understanding in which sentences are translated into basic concepts expressed as a small set of semantic primatives.

Conflict Resolution: Selecting a procedure from a conflict set of applicable competing procedures or rules.

Conflict Set: The set of rules which matches some data or pattern in the global data base.

Conjunct: One of several subproblems. Each of the component formulas in a logical conjunction.

Conjunction: A problem composed of several subproblems. A logical formula built by connecting other formulas by logical AND's.

Connectives: Operators (e.g., AND, OR) connecting statements in logic so that the truth-value of the composite is determined by the truth-value of the components.

Consequent: The right side of a production rule. The result of applying a procedure.

Constraint Propagation: A method for limiting search by requiring that certain constraints be satisified. It can also be viewed as a mechanism for moving information between subproblems.

Context: The set of circumstances or facts that define a particular situation, event, etc. The portion of the situation that remains the same when an operator is applied in a problem solving situation.

Control Structure: Reasoning strategy. The strategy for manipulating the domain knowledge to arrive at a problem solution.

D

Data Base: An organized collection of data about some subject.

Data Base Management System: A computer system for the storage and retrieval of information about some domain.

Data-Driven: A forward reasoning, bottom-up, problem solving approach.

Data Structure: The form in which data is stored in a computer.

Debugging: Correcting errors in a plan.

DEC: Digital Equipment Company.

Declarative Knowledge Representation: Representation of facts and assertions.

Deduction: A process of reasoning in which the conclusion follows from the premises given.

Default Value: A value to be used when the actual value is unknown.

Depth-First Search: A search that proceeds from the root node to one of the successor nodes and then to one of that node's successor nodes, etc., until a solution is reached or the search is forced to backtrack.

Difference Reduction: "Means-Ends" analysis. An approach to problem solving that tries to solve a problem by iteratively applying operators that will reduce the difference between the current state and the goal state.

Directed Graph: A knowledge representation structure consisting of nodes (representing, for example, objects) and directed connecting arcs (labeled edges, representing, for example, relations).

Disproving: An attempt to prove the impossibility of a hypothesized conclusion (theorem) or goal.

Domain: The problem area of interest; e.g., bacterial infections, prospecting, and VLSI design.

E

Editor: A software tool to aid in modifying a software program.

Embed: To write a computer language on top of (embedded in) another computer language (such as LISP).

Emulate: To perform like another system.

Equivalent: Has the same truth value (in logic).

Evaluation Function: A function (usually heuristic) used to evaluate the merit of the various paths emanating from a node in a search tree.

Event-Driven: A forward chaining, problem solving approach based on the current problem status.

Expectation-Driven: Processing approaches that proceed by trying to confirm models, situations, states, or concepts anticipated by the system.

Expert System: A computer program that uses knowledge and reasoning techniques to solve problems normally requiring the abilities of human experts.

F

Fault Diagnosis: Determining the trouble source in an electromechanical system.

Fifth Generation Computer: A non-Von Neumann, intelligent, parallel processing form of computer now being pursued by Japan.

First Order Predicate Logic: A popular form of logic used by the AI community for representing knowledge and performing logical inference. First Order Predicate Logic permits assertions to be made about variables in a proposition.

Forward Chaining: Event-driven or data-driven reasoning.

Frame: A data structure for representing stereotyped objects or situations. A frame has slots to be filled for objects and relations appropriate to the situation.

FRANZLISP: The dialect of LISP developed at the University of California, Berkeley.

Functional Application: The generic task or function performed in an application.

Fuzzy Set: A generalization of set theory that allows for various degrees of set membership, rather than all or none.

G

Garbage Collection: A technique for recycling computer memory cells no longer in use.

General Problem Solver (GPS): The first problem solver (1957) to separate its problem solving methods from knowledge of the specific task being considered. The GPS problem solving approach employed was "means-ends analysis."

Generate and Test: A common form of state space search based on reasoning by elimination. The system generates possible solutions and the tester prunes those solutions that fail to meet appropriate criteria.

Global Data Base: Complete data base describing the specific problem, its status, and that of the solution process.

Goal Driven: A problem solving approach that works backward from the goal.

Goal Regression: A technique for constructing a plan by solving one conjunctive subgoal at a time, checking to see that each solution does not interfere with the other subgoals that have already been achieved. If interferences occur, the offending subgoal is moved to an earlier noninterfering point in the sequence of subgoal accomplishments.

Graph: A set of nodes connected by arcs.

H

Heuristic Search Techniques: Graph searching methods that use heuristic knowledge about the domain to help focus the search. They operate by generating and testing intermediate states along potential solution paths.

Heuristics: Rules of thumb or empirical knowledge used to help guide a problem solution.

Hierarchial Planning: A planning approach in which first a high-level plan is formulated considering only the important (or major) aspects. Then the major steps of the plan are refined into more detailed subplans.

Hierarchy: A system of things ranked one above the other.

Higher Order Language (HOL): A computer language (such as FORTRAN or LISP) requiring fewer statements than machine language and usually substantially easier to use and read.

Horn Clause: A set of statements joined by logical AND's. Used in PROLOG.

I

Identity: Two propositions (in logic) that have the same truth value.

Image Understanding (IU): Visual perception by a computer employing geometric modeling and the AI techniques of knowledge representation and cognitive processing to develop scene interpretations from image data. IU has dealt extensively with three-dimensional objects.

Implies: A connective in logic that indicates that if the first statement is true, the statement following is also true.

Individual: A nonvariable element (or atom) in logic that cannot be broken down further.

Infer: To derive by reasoning. To conclude or judge from premises or evidence.

Inference: The process of reaching a conclusion based on an initial set of propositions, the truths of which are known or assumed.

Inference Engine: Another name given to the control structure of an AI problem solver in which the control is separate from the knowledge.

Instantiation: Replacing a variable by an instance (an individual) that satisfies the system (or satisfies the statement in which the variable appears).

Intelligence: The degree to which an individual can successfully respond to new situations or problems. It is based on the individual's knowledge level and the ability to appropriately manipulate and reformulate that knowledge (and incoming data) as required by the situation or problem.

Intelligent Assistant: An AI computer program (usually an expert system) that aids a person in the performance of a task.

Interactive Environment: A computational system in which the user interacts (dialogues) with the system (in real time) during the process of developing or running a computer program.

Interface: The system by which the user interacts with the computer. In general, the junction between two components.

INTERLISP: A dialect of LISP (used at Stanford University) developed at BBN and XEROX-PARC.

Invoke: To place into action (usually by satisfying a precondition).

K

Knowledge Base: AI data bases that are not merely files of uniform content, but are collections of facts, inferences, and procedures, corresponding to the types of information needed for problem solution.

Knowledge Base Management: Management of a knowledge base in terms of storing, accessing, and reasoning with the knowledge.

Knowledge Engineering: The AI approach focusing on the use of knowledge (e.g., as in expert systems) to solve problems.

Knowledge Representation (KR): The form of the data structure used to organize the knowledge required for a problem.

Knowledge Source: An expert system component that deals with a specific area or activity.

L

Leaf: A terminal node in a tree representation.

Least Commitment: A technique for coordinating decision making with the availability of information, so that problem solving decisions are not made arbitrarily or prematurely, but are postponed until there is enough information.

List: A sequence of zero or more elements enclosed in a pair of parentheses, where each element is either an atom (an indivisible element) or a list.

List Processing Language (LISP): The basic AI programming language.

Logical Operation: Execution of a single computer instruction.

Logical Representation: Knowledge representation by a collection of logical formulas (usually in First Order Predicate Logic) that provide a partial description of the world.

M

MACLISP: A dialect of LISP developed at M.I.T.

Means-Ends Analysis: A problem solving approach (used by GPS) in which problem solving operators are chosen in an iterative fashion to reduce the difference between the current problem solving state and the goal state.

Meta-Rule: A higher level rule used to reason about lower level rules.

Microcode: A computer program at the basic machine level.

Model Driven: A top-down approach to problem solving in which the inferences to be verified are based on the domain model used by the problem solver.

Modus Ponens: A mathematical form of argument in deductive logic. It has the form: If A is true, then B is true.
A is true.
Therefore, B is true.

N

Natural Deduction: Informal reasoning.

Natural Language Interface (NLI): A system for communicating with a computer by using a natural language.

Natural Language Processing (NLP): Processing of natural language (e.g., English) by a computer to facilitate communication with the computer or for other purposes such as language translation.

Natural Language Understanding (NLU): Response by a computer based on the meaning of a natural language input.

Negate: To change a proposition into its opposite.

Node: A point (representing such aspects as the system state or an object) in a graph connected to other points in the graph by arcs (usually representing relations).

Nonmonotonic Logic: A logic in which results are subject to revision as more information is gathered.

O

Object-Oriented Programming: A programming approach focused on objects which communicate by message passing. An object is considered to be a package of information and descriptions of procedures that can manipulate that information.

Operators: Procedures or generalized actions that can be used for changing situations.

P

Parallel Processing: Simultaneous processing, as opposed to the sequential processing in a conventional (Von Neumann) type of computer architecture.

Path: A particular track through a state graph.

Pattern Directed Invocation: The activation of procedures by matching their antecedent parts to patterns present in the global data base (the system status).

Pattern Matching: Matching patterns in a statement or image against patterns in a global data base, templates, or models.

Pattern Recognition: The process of classifying data into predetermined categories.

Perception: The process of classifying data into predetermined categories.

Personal AI Computer: New, small, interactive, stand-alone computers for use by an AI researcher in developing AI programs. Usually specifically designed to run an AI language such as LISP.

Plan: A sequence of actions to transform an initial situation into a situation satisfying the goal conditions.

Portability: The ease with which a computer program developed in one programming environment can be transferred to another.

Predicate: That part of a proposition that makes an assertion (e.g., states a relation or attribute) about individuals.

Predicate Logic: A modification of Propositional Logic to allow the use of variables and functions or variables.

Prefix Notation: A list representation (used in LISP programming) in which the connective, function, or predicate is given before the arguments.

Premise: A first proposition on which subsequent reasoning rests.

Problem Reduction: A problem solving approach in which operators are used to change a single problem into several subproblems (which are usually easier to solve).

Problem Solving: A procedure using a control strategy to apply operators to a situation to try to achieve a goal.

Problem State: The condition of the problem at a particular instant.

Procedural Knowledge Representation: A representation of knowledge about the world by a set of procedures - small programs that know how to do specific things.

Production Rule: A modular knowledge structure representing a single chunk of knowledge, usually in If-Then or Antecedent-Consequent form. Popular in Expert Systems.

Programming Environment: The total programming setup that includes the interface, the languages, the editors, and other programming tools.

Programming in Logic (PROLOG): A logic-oriented AI language developed in France and popular in Europe and Japan.

Property List: A knowledge representation technique by which the state of the world is described by objects in the world via lists of their pertinent properties.

Proposition: A statement (in logic) that can be true or false.

Propositional Logic: An elementary logic that uses argument forms to deduce the truth or falsehood of a new proposition from known propositions.

Prototype: An initial model or system that is used as a base for constructing future models or systems.

Pseudoreduction: An approach to solving the difficult problem case where multiple goals must be satisfied simultaneously. Plans are found to achieve each goal independently and then integrated using the knowledge of how plan segments can be intertwined without destroying their important effects.

R

Recursive Operations: Operations defined in terms of themselves.

Relaxation Approach: An iterative problem solving approach in which initial conditions are propagated utilizing constraints until all goal conditions are adequately satisfied.

Relevant Backtracking (Dependency-Directed or Nonchronological Backtracking): Backtracking (during a search) not to the most recent choice point, but to the most relevant choice point.

Resolution: A general, automatic, syntactic method for determining if a hypothesized conclusion (theorem) follows from a given set of premises (axioms).

Root Node: The initial (apex) node in a tree representation.

Rule-Interpreter: The control structure for a production rule system.

S

Satisficing: Developing a satisfactory, but not necessarily optimum, solution.

Scheduling: Developing a time sequence of things to be done.

Scripts: Frame-like structures for representing sequences of events.

Search Space: The implicit graph representing all the possible states of the system which may have to be searched to find a solution. In many cases the search space is infinite. The term search space is also used for non-state-space representations.

Semantic: Of or relating to meaning.

Semantic Network: A knowledge representation for describing the properties and relations of objects, events, concepts, situations, or actions by a directed graph consisting of nodes and labeled edges (arcs connecting nodes).

Semantic Primitives: Basic conceptual units in which concepts, ideas, or events can be represented.

S-Expression: A symbolic expression. In LISP, a sequence of zero or more atoms or S-expressions enclosed in parentheses.

Slot: An element in a frame representation to be filled with designated information about the particular situation.

Software: A computer program.

Solution Path: A successful path through a search space.

Speech Recognition: Recognition by a computer (primarily by pattern matching) of spoken words or sentences.

Speech Synthesis: Developing spoken speech from text or other representations.

Speech Understanding: Speech perception by a computer.

SRI Vision Module: An important object recognition, inspection, orientation, and location research vision system developed at SRI. This system converted the scene into a binary image and extracted the calculated needed vision parameters in real time, as it sequentially scanned the image line by line.

State Graph: A graph in which the nodes represent the system state and the connecting arcs represent the operators which can be used to transform the state from which the arcs emanate to the state at which they arrive.

Stereotyped Situation: A generic, recurrent situation such as "eating at a restaurant" or "driving to work."

Subgoals: Goals that must be achieved to achieve the original goal.

Subplan: A plan to solve a portion of the problem.

Subproblems: The set of secondary problems that must be solved to solve the original problem.

Syllogism: A deductive argument in logic whose conclusion is supported by two premises.

Symbolic: Relating to the substitution of abstract representations (symbols) for concrete objects.

Syntax: The order or arrangement (e.g., the grammar of a language).

T

Terminal Node (Leaf Node): The final node emanating from a branch in a tree or graph representation.

Theorem: A proposition, or statement, to be proved based on a given set of premises.

Theorem Proving: A problem solving approach in which a hypothesized conclusion (theorem) is validated using deductive logic.

Time-Sharing: A computer environment in which multiple users can use the computer virtually simultaneously via a program that time-allocates the use of computer resources among the users in a near-optimum manner.

Top-Down Approach: An approach to problem solving that is goal-directed or expectation-guided based on models or other knowledge. Sometimes referred to as "Hypothesize and Test."

Top-Down Logic: A problem solving approach used in production systems, where production rules are employed to find a solution path by chaining backwards from the goal.

Tree Structure: A graph in which one node, the root, has no predecessor node, and all other nodes have exactly one predecessor. For a state space representation, the tree starts with a root node (representing the initial problem situation). Each of the new states that can be produced from this initial state by application of a single operator is represented by a successor node of the root node. Each successor node branches in a similar way until no further states can be generated or a solution is reached. Operators are represented by the directed arcs from the nodes to their successor nodes.

Truth Maintenance: A method of keeping track of beliefs (and their justifications) developed during problem solving so that if contradictions occur, the incorrect beliefs or lines of reasoning, and all conclusions resulting from them, can be retracted.

Truth Value: One of the two possible values - True or False - associated with a proposition in logic.

U

Unification: The name for the procedure for carrying out instantiations. In unification, the attempt is to find substitutions for variables that will make two atoms identical.

V

Variable: A quantity or function that may assume any given value or set of values.

Von Neumann Architecture: The current standard computer architecture that uses sequential processing.

W

World Knowledge: Knowledge about the world (or domain of interest).

World Model: A representation of the current situation.

SPACE SYSTEMS TERMINOLOGY

Any field develops a certain amount of specialized terminology or "jargon" in order to convey complicated ideas in a terse manner. Descriptions of space vehicles and systems are often replete with such jargon. The writers of this report have tried, as much as possible, to avoid specialized terminology. Some of the terms used by the specialists are very helpful, however, and are difficult to avoid without cumbersome substitutions. The following definitions and examples will aid in understanding some of the terms used in this report.

Co-orbiting: Said of a satellite orbiting in an orbit close to and readily accessible to the Space Station orbit.

Fail-safe/fail-operational: Said of a design approach for a spacecraft component in which a failure of the component will result in a condition that is operational if possible or at least safe.

Fault-tolerant: A feature of a (computer) system which allows some level of operation to continue even after a fault has occurred.

Hooks: Provisions made in computer software upon which future capability can be built or "hung." This can save expensive restructuring of the software when additional capability is needed. This practice is analogous to leaving a slot in a concert program which can be filled when the details of the performer and the selection to be played have been worked out.

Human/Machine Interface: The devices, programs, and procedures by which a human interacts with a machine.

Model: A representation, frequently done analytically with a computer, of some physical situation which aids in understanding. For example, an analytical representation of the response of a proposed robot to external stimuli could aid in the design of the robot.

Phases B, C, D: Stages in implementing a space project; respectively, (B) preliminary design and definition, (C) detailed design, and (D) construction.

Platform: A flight element of the Space Station Program which carries out special tasks in a separate orbit from that of the station and which is serviced in some way by the station.

Proximity Sensor: A sensing device that detects when an object comes within a specified distance of the device.

Retro-Fit: The retroactive modification of a system or device after it has been put in service.

Scars: Provisions made in hardware to accommodate future features. This is analogous to reinforcing the end of a driveway when one knows that a garage is to be erected later on. In a Space Station example, provisions could be made for pads to which an inspection robot would later be attached.

Teleoperation: The execution of physical tasks by a manipulating device under human control.

Telepresence: The concept of remotely controlled manipulation in which the manipulators at the worksite have the dexterity to perform normal human functions and the operator at the control site has sensory feedback sufficient to provide the feeling of being present at the remote site where the action is taking place.

Trade (or Trade-Off Study): An assessment of the optimum combination of elements or design to achieve a desired goal. For example, increasing the precision of a thrust control device might increase the weight of the device but save on fuel consumption and thus reduce overall weight.

Transparent: Said of a change (to a computer program) not visible or readily apparent to the primary user.

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16. Abstract

In response to Public Law 98-371, dated July 18, 1984, the NASA Advanced Technology Advisory Committee has studied automation and robotics for use in the Space Station and prepared this report to the House and Senate Committees on Appropriations. The report is divided into two volumes:

The Executive Overview, Volume I, presents the major findings of the study and recommends to NASA principles for advancing automation and robotics technologies for the benefit of the Space Station and of the U.S. Economy in general.

The Technical Report, Volume II this document, provides background information on automation and robotics technologies and their potential and documents:

The relevant aspects of Space Station design;

Representative examples of automation and robotics; applications

The state of the technology and advances needed; and

Considerations for technology transfer to U.S. industry and for space commercialization

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